А.И. Матяшевская, Е.В. Тиден

ILLUMINATING PHYSICS:

part 5

Учебное пособие

Саратов

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

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Рецензент:

Кандидат философских наук Шилова С.А.

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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: *Quanta Magazine, Aeon, Nautilus, Wired Magazine, Racked*) 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. New Quantum Paradox Clarifies Where Our Views of Reality Go Wrong

<u>Exercise I.</u>

Say what Russian words help to guess the meaning of the following words: microscopic, dispute, real, computers, potentially, discriminate, federal, institute, universal, macromolecules

<u>Exercise II.</u>

Make sure you know the following words and word combinations.

decidedly, unscathed, to infer, consistency, untenable, conundrum, attribute, formidable, malleable

New Quantum Paradox Clarifies Where Our Views of Reality Go Wrong

A thought experiment has shaken up the world of quantum foundations, forcing physicists to clarify how various quantum interpretations (such as many-worlds and the Copenhagen interpretation) abandon seemingly sensible assumptions about reality.

That quantum mechanics makes astonishingly accurate predictions about the nature of the world at microscopic scales. What has been in dispute for nearly a century is just what it's telling us about what exists, what is real. There are myriad interpretations that offer their own take on the question, each requiring us to buy into certain as-yet-unverified claims — hence assumptions — about the nature of reality. Now, a new thought experiment is shaking the foundations of quantum physics. The experiment is decidedly strange. For example, it requires making measurements that can erase any memory of an event that was just observed. While this isn't possible with humans, quantum computers could be used to carry out this weird experiment and potentially discriminate between the different interpretations of quantum physics. The experiment, designed by Daniela Frauchiger and Renato Renner, of the Swiss Federal Institute of Technology Zurich, involves a set of assumptions that on the face of it seem entirely reasonable. But the experiment leads to contradictions, suggesting that at least one of the assumptions is wrong. The choice of which assumption to give up has implications for our understanding of the quantum world and points to the possibility that quantum mechanics is not a universal theory, and so cannot be applied to complex systems such as humans. Quantum physicists are notoriously divided when it comes to the correct interpretation of the equations that are used to describe quantum goings-on. But in the new thought experiment, no view of the quantum world comes through unscathed. Each one falls afoul of one or another assumption. Could something entirely new await us in our search for an uncontroversial description of reality? Quantum theory works extremely well at the scale of photons, electrons, atoms, molecules, even macromolecules. But is it applicable to systems that are much, much larger than macromolecules? "We have not experimentally established the fact that quantum mechanics applies on larger scales, and larger means even something the size of a virus or a little cell," Renner said. "In particular, we don't know whether it extends to objects the size of humans and even lesser, whether it extends to objects the size of black holes." Despite this lack of empirical evidence, physicists think that quantum mechanics can be used to describe systems at all scales — meaning it's universal. To test this assertion, Frauchiger and Renner came up with their thought experiment, which is an extension of something the physicist Eugene Wigner first dreamed up in the 1960s. The new experiment shows that, in a quantum world, two people can end up disagreeing about a seemingly irrefutable result, such as the outcome of a coin toss, suggesting something is amiss with the assumptions we make about quantum reality.

In standard quantum mechanics, a quantum system such as a subatomic particle is represented by a mathematical abstraction called the wave function. Physicists calculate how the particle's wave function evolves with time. But the wave function does not give us the exact value for any of the particle's properties, such as its position. If we want to know where the particle is, the wave function's value at any point in space and time only lets us calculate the probability of finding the particle at that point, should we choose to look. Before we look, the wave function is spread out, and it accords different probabilities for the particle being in different places. The particle is said to be in a quantum superposition of being in many places at once. More generally, a quantum system can be in a superposition of states, where "state" can refer to other properties, such as the spin of a particle. Much of the Frauchiger-Renner thought experiment involves manipulating complex quantum objects — maybe even humans — that end up in superpositions of states. The experiment has four agents: Alice, Alice's friend, Bob, and Bob's friend. Alice's friend is inside a lab making measurements on a quantum system, and Alice is outside, monitoring both the lab and her friend. Bob's friend is similarly inside another lab, and Bob is observing his friend and the lab, treating them both as one system. Inside the first lab, Alice's friend makes a measurement on what is effectively a coin toss designed to come up heads one-third of the time and tails two-thirds of the time. If the toss comes up heads, Alice's friend prepares a particle with spin pointing down, but if the toss comes up tails, she prepares the particle in a superposition of equal parts spin UP and spin DOWN. Alice's friend sends the particle to Bob's friend, who measures the spin of the particle. Based on the result, Bob's friend can now make an assertion about what Alice's friend saw in her coin toss. If he finds the particle spin to be UP, for example, he knows the coin came up tails. The experiment continues. Alice measures the state of her friend and her lab, treating all of it as one quantum system, and uses quantum theory to make predictions. Bob does the same with his friend and lab. Here comes the first assumption: An agent can analyze another system, even a complex one including other agents, using quantum mechanics. In other words, quantum theory is universal, and everything in the universe, including entire laboratories (and the scientists inside them), follows the rules of quantum mechanics. This assumption allows Alice to treat her friend and the lab as one system and make a special type of measurement, which puts the entire lab, including its contents, into a superposition of states. This is not a simple measurement, and herein lies the thought experiment's weirdness. The process is best understood by considering a single photon that's in a superposition of being polarized horizontally and vertically. Say you measure the polarization and find it to be vertically polarized. Now, if you keep checking to see if the photon is vertically polarized, you will always find that it is. But if you measure the vertically polarized photon to see if it is polarized in a different direction, say at a 45-degree angle to the vertical, you'll find that there's a 50 percent chance that it is, and a 50 percent chance that it isn't. Now if you go back to measure what you thought was a vertically polarized photon, you'll find there's a chance that it's no longer vertically polarized at all — rather, it's become horizontally polarized. The 45-degree measurement has put the photon back into a superposition of being polarized horizontally and vertically. This is all very fine for a single particle, and such measurements have been verified in actual experiments. But in the thought experiment, Frauchiger and Renner want to do something similar with complex systems. As this stage in the experiment, Alice's friend has already seen the coin coming up either heads or tails. But Alice's complex measurement puts the lab, friend included, into a superposition of having seen heads and tails. Given this weird state, it's just as well that the experiment does not demand anything further of Alice's friend. Alice, however, is not done. Based on her complex measurement, which can come out as either YES or NO, she can infer the result of the measurement made by Bob's friend. Say Alice got YES for an answer. She can deduce using quantum mechanics that Bob's friend must have found the particle's spin to be UP, and therefore that Alice's friend got tails in her coin toss. This assertion by Alice necessitates another assumption about her use of quantum theory. Not only does she reason about what she knows, but she reasons about how Bob's friend used quantum theory to arrive at his conclusion about the result of the coin toss. Alice makes that conclusion her own. This assumption of consistency argues that the predictions made by different agents using quantum theory are not contradictory. Meanwhile, Bob can make a similarly complex measurement on his friend and his lab, placing them in a quantum superposition. The answer can again be YES or NO. If Bob gets YES, the measurement is designed to let him conclude that Alice's friend must have seen heads in her coin toss. It's clear that Alice and Bob can make measurements and compare their assertions about the result of the coin toss. But this involves another assumption: If an agent's measurement says that the coin toss came up heads, then the opposite fact — that the coin toss came up tails — cannot be simultaneously true.

The setup is now ripe for a contradiction. When Alice gets a YES for her measurement, she infers that the coin toss came up tails, and when Bob gets a YES for his measurement, he infers the coin toss came up heads. Most of the time, Alice and Bob will get opposite answers. But Frauchiger and Renner showed that in 1/12 of the cases both Alice and Bob will get a YES in the same run of the experiment, causing them to disagree about whether Alice's friend got a heads or a tails. "So, both of them are talking about the past event, and they are both sure what it was, but their statements are exactly opposite," Renner said. "And that's the contradiction. That shows something must be wrong." This led Frauchiger and Renner to claim that one of the three assumptions that underpin the thought experiment must be incorrect. "The science stops there. We just know one of the three is wrong, and we cannot really give a good argument as to which one is violated," Renner said. "This is now a matter of interpretation and taste." Fortunately, there are a wealth of interpretations of quantum mechanics, and almost all of them have to do with what happens to the wave function upon measurement. Take a particle's position. Before measurement, we can only talk in terms of the probabilities of, say, finding the particle somewhere. Upon measurement, the particle assumes a definite location. In the Copenhagen interpretation, measurement causes the wave function to collapse, and we cannot talk of properties, such as a particle's position, before collapse. Some physicists view the Copenhagen interpretation as an argument that properties are not real until measured. This form of "anti-realism" was anathema to Einstein, as it is to some quantum physicists today. And so is the notion of a measurement causing the collapse of the wave function, particularly because the Copenhagen interpretation is unclear about exactly what constitutes a measurement. Alternative interpretations or theories mainly try to either advance a realist view — that quantum systems have properties independent of observers and measurements — or avoid a measurement-induced collapse, or both. For example, the many-worlds interpretation takes the evolution of the wave function at face value and denies that it ever collapses. If a quantum coin toss can be either heads or tails, then in the many-worlds scenario, both outcomes happen, each in a different world. Given this, the assumption that there is only one outcome for a measurement, and that if the coin toss is heads, it cannot simultaneously be tails, becomes untenable. In many-worlds, the result of the coin toss is both heads and tails, and thus the fact that Alice and Bob can sometimes get opposite answers is not a contradiction. "I have to admit that if you had asked me two years ago, I'd have said our experiment just shows that many-worlds is actually a good interpretation and you should give up the requirement that measurements have only a single outcome", Renner said. This is also the view of the theoretical physicist David Deutsch of the University of Oxford. Deutsch thinks the thought experiment will continue to support many-worlds. "My take is likely to be that it kills wave-function-collapse or single-universe versions of quantum theory, but they were already stone dead," he said. "I'm not sure what purpose it serves to attack them again with bigger weapons." Renner, however, now thinks the assumption most likely to be invalid is the idea that quantum mechanics is universally applicable. This assumption is violated, for example, by so-called spontaneous collapse theories that argue — as the name suggests — for a spontaneous and random collapse of the wave function, but one that is independent of measurement. These models ensure that small quantum systems, such as particles, can remain in a superposition of states almost forever, but as systems get more massive, it gets more and more likely that they will spontaneously collapse to a classical state. Measurements merely discover the state of the collapsed system. In spontaneous collapse theories, quantum mechanics can no longer to be applied to systems larger than some threshold mass. And while these models have yet to be empirically verified, they haven't been ruled out either. Nicolas Gisin of the University of Geneva favors spontaneous collapse theories as a way to resolve the contradiction in the Frauchiger-Renner experiment. "My way out of their conundrum is clearly by saying, 'No, at some point the superposition principle no longer holds,'" he said.

If you want to hold on to the assumption that quantum theory is universally applicable, and that measurements have only a single outcome, then you've got to let go of the remaining assumption, that of consistency: The predictions made by different agents using quantum theory will not be contradictory. Using a slightly altered version of the Frauchiger-Renner experiment, Leifer has shown that this final assumption must go if Copenhagen-style theories hold true. In Leifer's analysis, these theories share certain attributes, in that they are universally applicable, anti-realistic (meaning that quantum systems don't have well-defined properties, such as position, before measurement) and complete (meaning that there is no hidden reality that the theory is failing to capture). Given these attributes, his work implies that there is no single outcome of a given measurement that's objectively true for all observers. So if a detector clicked for Alice's friend inside the lab, then it's an objective fact for her, but not so for Alice, who is outside the lab modeling the entire lab using quantum theory. The results of measurements depend on the perspective of the observer. The Frauchiger-Renner experiment generates contradictions among a set of three seemingly sensible assumptions. The effort to explicate how various interpretations of quantum theory violate the assumptions has been "an extremely useful exercise," said Rob Spekkens of the Perimeter Institute for Theoretical Physics in Waterloo, Canada. "This thought experiment is a great lens through which to examine the differences of opinions between different camps on the interpretation of quantum theory," Spekkens said. Experimentalists are thinking about how to implement the thought experiment, in the hope of further illuminating the problem. But it will be a formidable task, because the experiment makes some weird demands. For example, when Alice makes a special measurement on her friend and her lab, it puts everything, the friend's brain included, into a superposition of states. Nonetheless, some researchers are not averse to thinking that maybe, one day, the experiment could be done using complex quantum computers as the agents inside the labs (acting as Alice's friend and Bob's friend). In principle, the time evolution of a quantum computer can be reversed. One possibility is that such an experiment will replicate the predictions of standard quantum mechanics even as quantum computers get more and more complex. But it may not. Another alternative is that at some point while we develop these quantum computers, we hit the boundary of the superposition principle and find that actually quantum mechanics is not universal. Leifer, for his part, is holding out for something new. He likens the current situation with quantum mechanics to the time before Einstein came up with his special theory of relativity. Experimentalists had found no sign of the ether — the medium through which light waves were thought to propagate in a Newtonian universe. Einstein argued that there is no ether. Instead he showed that space and time are malleable. Quantum mechanics is in a similar situation now, he thinks. "It's likely that we are making assumption about the way the world has to be that just isn't true," Leifer said. "Once we change that, once we modify that assumption, everything would suddenly fall into place. Can I tell you what's a plausible candidate for such an assumption? Well, if I could, I would just be working on that theory."

Adapted from Quanta Magazine

Exercise III.

Fill in the gaps.

1) Most ______________ people agree that an overhaul of the immigration system is needed.

2) Then, with the next wave of technology, the vision becomes _________________ futuristic.

3) It seems _________________ to assume a correlation between wealth and entrepreneurship.

4) Primary school teacher Sarah Stoneley has so far survived her new job _________________.

5) I have to agree with the _____________ of the author that house prices have to fall.

6) One might also ________________ that there is increasing competition for jobs from non MBAs.

7) A calm, peaceful home where there are firm limits and ______________ would be best.

8) Progress has been slow, in part because Taliesin presents a particular ______________.

9) He showed almost superhuman courage and was, in many respects, a _____________ man.

10) Metals are usually _____________ and shiny, that is they reflect most of incident light.

Exercise IV.

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

to buy into, to rule out, to shake up, to make accurate predictions about, at microscopic scales, be in dispute, to erase any memory of an event, to carry out this weird experiment, to lead to contradictions, to give up

Exercise V.

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

sensible	wrongly or inappropriately
to discriminate	strikingly out of the ordinary
reasonable	a confident and forceful statement of fact or belief
assertion	give or grant someone (power, status, or recognition)
irrefutable	inspiring fear or respect through being impressively large, powerful, intense, or capable
amiss	impossible to deny or disprove
formidable	chosen in accordance with wisdom or prudence; likely to be of benefit
malleable	recognize a distinction; differentiate
to accord	having sound judgment; fair and sensible
weirdness	able to be hammered or pressed permanently out of shape without breaking or cracking

Exercise VI.

Identify the part of speech the words belong to: experiment, foundations, various, interpretations, sensible, assumptions, accurate, predictions, microscopic, real

Exercise VII.

Match the words to make word combinations:

uncontroversial	predictions
correct	interpretations
Federal	computers
universal	interpretation
complex	Institute
black	theory
quantum	scales
microscopic	holes
accurate	description
myriad	systems

Exercise VIII.

Summarize the article “New Quantum Paradox Clarifies Where Our Views of Reality Go Wrong”

2. The blind spot

Exercise I.

Say what Russian words help to guess the meaning of the following words: total, system, positions, absolute, image, control, distance, materialism, elementary, moments

Exercise II.

Make sure you know the following words and word combinations.
ill-posed, data-point, conundrum, immediacy, arbitrary, bluntly, to circumscribe, to render, to intertwine, nourished, sensibility

The blind spot

It's tempting to think science gives a God's-eye view of reality. But we forget the place of human experience at our peril

The problem of time is one of the greatest puzzles of modern physics. The first bit of the conundrum is cosmological. To understand time, scientists talk about finding a 'First Cause' or 'initial condition' – a description of the Universe at the very beginning (or at 'time equals zero'). But to determine a system's initial condition, we need to know the total system. We need to make measurements of the positions and velocities of its constituent parts, such as particles, atoms, fields and so forth. This problem hits a hard wall when we deal with the origin of the Universe itself, because we have no view from the outside. We can't step outside the box in order to look within, because the box is all there is. A First Cause is not only unknowable, but also scientifically unintelligible. The second part of the challenge is philosophical. Scientists have taken physical time to be the only real time – whereas experiential time, the subjective sense of time's passing, is considered a cognitive fabrication of secondary importance. The young Albert Einstein made this position clear in his debate with philosopher Henri Bergson in the 1920s, when he claimed that the physicist's time is the only time. With age, Einstein became more circumspect. Up to the time of his death, he remained deeply troubled about how to find a place for the human experience of time in the scientific worldview. These quandaries rest on the presumption that physical time, with an absolute starting point, is the only real kind of time. But what if the question of the beginning of time is ill-posed? Many of us like to think that science can give us a complete, objective description of cosmic history, distinct from us and our perception of it. But this image of science is deeply flawed. In our urge for knowledge and control, we've created a vision of science as a series of discoveries about how reality is in itself, a God's-eye view of nature. Such an approach not only distorts the truth, but creates a false sense of distance between ourselves and the world. That divide arises from what we call the Blind Spot, which science itself cannot see. In the Blind Spot sits experience: the sheer presence and immediacy of lived perception. Behind the Blind Spot sits the belief that physical reality has absolute primacy in human knowledge, a view that can be called scientific materialism. Elementary particles, moments in time, genes, the brain – all these things are assumed to be fundamentally real. By contrast, experience and consciousness are taken to be secondary. The scientific task becomes about figuring out how to reduce them to something physical, such as the behaviour of neural networks, the architecture of computational systems, or some measure of information.

This framework faces two intractable problems. The first concerns scientific objectivism. We never encounter physical reality outside of our observations of it. This doesn't mean that scientific knowledge is arbitrary, or a mere projection of our own minds. On the contrary, some models and methods of investigation work much better than others, and we can test this. But these tests never give us nature as it is in itself, outside our ways of seeing and acting on things. Experience is just as fundamental to scientific knowledge as the physical reality it reveals. The second problem concerns physicalism. According to the most reductive version of physicalism, science tells us that everything, including life, the mind and consciousness, can be reduced to the behaviour of the smallest material constituents. You're nothing but your neurons, and your neurons are nothing but little bits of matter. Here, life and the mind are gone, and only lifeless matter exists. To put it bluntly, the claim that there's nothing but physical reality is either false or empty. The point is that physical science doesn't include an account of experience; but we know that experience exists, so the claim that the only things that exist are what physical science tells us is false. On the other hand, if 'physical reality' means reality according to some future and complete physics, then the claim that there is nothing else but physical reality is empty, because we have no idea what such a future physics will look like, especially in relation to consciousness. Objectivism and physicalism are philosophical ideas, not scientific ones – even if some scientists espouse them. They don't logically follow from what science tells us about the physical world, or from the scientific method itself. By forgetting that these perspectives are a philosophical bias, not a mere data-point, scientific materialists ignore the ways that immediate experience and the world can never be separated.

We're not alone in our opinions. Our account of the Blind Spot is based on the work of two major philosophers and mathematicians, Edmund Husserl and Alfred North Whitehead. Husserl argued that experience is the source of science. It's absurd, in principle, to think that science can step outside it. The 'life-world' of human experience is the 'grounding soil' of science, and the crisis of modern scientific culture – what we are calling the Blind Spot – comes from forgetting its primacy. Whitehead suggested that science relies on a faith in the order of nature that can't be justified by logic. That faith rests directly on our immediate experience. He argued that what we call 'reality' is made up of evolving processes that are equally physical and experiential.

Nowhere is the materialistic bias in science more apparent than quantum physics, the science of atoms and subatomic particles Today, interpretations of quantum mechanics disagree about what matter is, and what our role is with respect to it. These differences concern the so-called 'measurement problem': how the wave function of the electron reduces from a superposition of several states to a single state upon observation. For several schools of thought, quantum physics doesn't give us access to the way the world fundamentally is in itself. Rather, it only lets us grasp how matter behaves in relation to our interactions with it. According to the so-called Copenhagen interpretation of Niels Bohr, for example, the wave function has no reality outside of the interaction between the electron and the measurement device. Other approaches, such as the many worlds interpretation, seek to preserve an observer-independent status for the wave function. But this comes at the cost of adding features such as unobservable parallel universes. In short, there’s still no simple way to remove our experience as scientists from the characterisation of the physical world. This brings us back to the Blind Spot. When we look at the objects of scientific knowledge, we don’t tend to see the experiences that underpin them. We do not see how experience makes their presence to us possible. Because we lose sight of the necessity of experience, we erect a false idol of science as something that bestows absolute knowledge of reality, independent of how it shows up and how we interact with it.

Scientific materialists will argue that the scientific method enables us to get outside of experience and grasp the world as it is in itself. As will be clear by now, we disagree; indeed, we believe that this way of thinking misrepresents the very method and practice of science. In general terms, here’s how the scientific method works. First, we set aside aspects of human experience on which we can’t always agree, such as how things look or taste or feel. Second, using mathematics and logic, we construct abstract, formal models that we treat as stable objects of public consensus. Third, we intervene in the course of events by isolating and controlling things that we can perceive and manipulate. Fourth, we use these abstract models and concrete interventions to calculate future events. Fifth, we check these predicted events against our perceptions. An essential ingredient of this whole process is technology: machines – our equipment – that standardise these procedures, amplify our powers of perception, and allow us to control phenomena to our own ends. The Blind Spot arises when we start to believe that this method gives us access to unvarnished reality. Scientific models are idealisations, not actual things in the world.

Galileo’s model of a frictionless plane, for example; the Bohr model of the atom with a small, dense nucleus with electrons circling around it in orbits like planets around a sun; evolutionary models of isolated populations – all of these exist in the scientist’s mind, not in nature. They are abstract mental representations, not mind-independent entities. Their power comes from the fact that they’re useful for helping to make testable predictions. But these, too, never take us outside experience, for they require specific kinds of perceptions performed by highly trained observers. For these reasons, scientific ‘objectivity’ can’t stand outside experience; in this context, ‘objective’ simply means something that’s true to the observations agreed upon by a community of investigators using certain tools. Science is essentially a highly refined form of human experience, based on our capacities to observe, act and communicate. So the belief that scientific models correspond to how things truly are doesn’t follow from the scientific method. Instead, it comes from an ancient impulse – one often found in monotheistic religions – to know the world as it is in itself, as God does. The contention that science reveals a perfectly objective ‘reality’ is more theological than scientific. Recent philosophers of science argue that science doesn’t culminate in a single picture of a theory-independent world. Rather, various aspects of the world – from chemical interactions to the growth and development of organisms, brain dynamics and social interactions – can be more or less successfully described by partial models. These models are always bound to our observations and actions, and circumscribed in their application.

‘Time’ will always have a human dimension - the best we can aim for is to construct a scientific cosmological account that is consistent with what we can measure and know of the Universe from inside. The account can't ever be a final or complete description of cosmic history. Rather, it must be an ongoing, self-correcting narrative. 'Time' is the backbone of this narrative; our experience of time is necessary to make the narrative meaningful. With this insight, it seems it's the physicist's time that is secondary; it's merely a tool to describe the changes we're able to observe and measure in the natural world. The time of the physicist, then, depends for its meaning on our experience of time. We can now appreciate the deeper significance of our three scientific conundrums – the nature of matter, consciousness and time. They all point back to the Blind Spot and the need to reframe how we think about science. When we try to understand reality by focusing only on physical things outside of us, we lose sight of the experiences they point back to. The deepest puzzles can't be solved in purely physical terms, because they all involve the unavoidable presence of experience in the equation. There's no way to render 'reality' apart from experience, because the two are always intertwined. To finally 'see' the Blind Spot is to wake up from a delusion of absolute knowledge. It's also to embrace the hope that we can create a new scientific culture, in which we see ourselves both as an expression of nature and as a source of nature's self-understanding. We need nothing less than a science nourished by this sensibility for humanity to flourish in the new millennium.

Adapted from Aeon

Exercise III.

Fill in the gaps.

1) Americans have been bemoaning the state of education since the 1950s, when it was believed our failing schools put us ______________ during the Cold War.

2) The largest and most _________________ failures have been with the public utilities.

3) I hope by next month you'll be back to your usual cheerful and ______________ self.

4) For the prime minister and his supporters, the _____________ brought its own trouble.

5) For now, neither side feels compelled to start negotiations with any _________________.

6) It is the combination of the two that has rendered the situation so _____________.

7) Unlike those other choices, which were at least semi-________________, this one is not.

8) Any attempt to _________________ the individual's freedom to choose must be viewed with scepticism.

9) Life and death, love and human invention are explored as the two stories ________________.

10) He has the technical skills of a grown-up, and the _________________ of an adolescent.

Exercise IV.

Make up sentences of your own with the following word combinations: at peril, to make measurements of, constituent parts, to hit a hard wall, secondary importance, with age, up to the time of his death, remain deeply troubled about, in the scientific worldview, to rest on

Exercise V.

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

circumspect	hard to control or deal with
quandary	come between so as to prevent or alter a result or course of events
shear	adopt or support (a cause, belief, or way of life)
immediacy	not covered with varnish
intractable	the quality of bringing one into direct and instant involvement with something, giving rise to a sense of urgency or excitement
to espouse	have something cut off
to bestow	heated disagreement
to intervene	a state of perplexity or uncertainty over what to do in a difficult situation
contention	confer or present (an honor, right, or gift)
unvarnished	wary and unwilling to take risks

Exercise VI.

Identify the part of speech the words belong to.

unintelligible, physicalism, assertion, initial, condition, description, total, system, measurements, positions

Exercise VII.

Match the words to make word combinations:

scientific	time
blind	spot
starting	fabrication
God's-eye	worldview
false	point
absolute	view of nature
scientific	sense
cognitive	materialism
real	primacy
blind	spot

Exercise VIII.

Summarize the article "The blind spot".

3. Paradigms lost

Exercise I.

Say what Russian words help to guess the meaning of the following words: paradigms, dynamic, biosphere, planet, cosmos, synthesise, chemicals, manipulate, triumph, medicine

Exercise II.

Make sure you know the following words and word combinations.
robust, humdrum, albeit, scourge, pertussis, to linger, astounding, to proceed, clad, to dishearten

Paradigms lost

Science is not a 'body of knowledge' – it's a dynamic, ongoing reconfiguration of knowledge and must be free to change

Coming from a scientist, this sounds smug, but here it is: science is one of humanity's most noble and successful endeavours, and our best way to learn how the world works. We know more than ever about our own bodies, the biosphere, the planet and even the cosmos. We take pictures of Pluto, unravel quantum mechanics, synthesise complex chemicals and can peer into (as well as manipulate) the workings of DNA, not to mention our brains and, increasingly, even our diseases. Sometimes science's very success causes trouble, it's true. Nuclear weapons – perhaps the most immediate threat to life on Earth – were a triumph for science. Then there are the paradoxical downsides of modern medicine, notably overpopulation, plus the environmental destruction that science has unwittingly promoted. But these are not the cause of the crisis faced by science today. Today science faces a crisis of legitimacy which is entirely centred on rampant public distrust and disavowal. A survey conducted with the American Association for the Advancement of Science reported that a mere 33 per cent of the American public accepted evolution. A standard line from politicians when asked about climate change is ‘I’m not a scientist’… as though that absolved them from looking at the facts. Vaccines have been among medical science’s most notable achievements (essentially eradicating smallpox and nearly eliminating polio, among other infectious scourges) but the anti-vaccination movement has stalled comparable progress against measles and pertussis. How can this be? Why must we scientists struggle to defend and promote our greatest achievements? There are many possible factors at work. In some cases, science conflicts with religious belief, in the political sphere, there is a conflict between scientific facts and short-term economic prospects (climate-change deniers tend to be not merely scientifically illiterate, but funded by CO2-emitting corporations). Anti-vaxxers are propelled by the lingering effect of a single discredited research report that continues to resonate with people predisposed to ‘alternative medicine’ and stubborn opposition to establishment wisdom.

The problems run deeper than this, however. Many scientific findings run counter to common sense and challenge our deepest assumptions about reality: the fact that even the most solid objects are composed at the subatomic level of mostly empty space, or the difficulty of conceiving things that go beyond everyday experience, such as vast temperatures, time scales, distances and speeds, or (as in the case of continental drift) exceedingly slow movements – not to mention the statistically verifiable but nonetheless unimaginable ability of natural selection, over time, to generate outcomes of astounding complexity. On top of this, we have the continuing paradox that the more we learn about reality, the less central and self-important is our own species. Yet one factor in the public distrust of science has been largely overlooked, and it goes to the heart of the scientific enterprise. The capacity for self-correction is the source of science's immense strength, but the public is unnerved by the fact that scientific wisdom isn't immutable. Scientific knowledge changes with great speed and frequency – as it should – yet public opinion drags with reluctance to be modified once established. And the rapid ebb and flow of scientific 'wisdom' has left many people feeling jerked around, confused, and increasingly resistant to science itself. In his hugely influential book, The Structure of Scientific Revolutions, the physicist and philosopher of science Thomas Kuhn argued that 'normal science' proceeds within certain reigning 'paradigms'. In other words, each scientific discipline is governed by an accepted set of theories and metaphysical assumptions, within which normal science operates. Periodically, when this rather humdrum 'puzzle solving' leads to results that are inconsistent with the regnant perspective, there follows a disruptive, exciting period of 'scientific revolution', after which a new paradigm is instituted and normal science can operate once more. Strangely, Kuhn argued that new paradigms do not necessarily offer a more accurate picture of the real world. This seems a peculiar claim: for example, in Kuhn's own field of astronomy, the Copernican view of a heliocentric solar system is clearly superior to the earlier geocentric one. Kuhn’s language has lent itself to an exaggerated sense of just how revolutionary a new paradigm is liable to be. When Newton said: ‘If I have seen farther, it is by standing on the shoulders of giants’, he wasn’t merely being modest; rather he was emphasising the extent to which science is cumulative, mostly building on past achievements rather than making quantum leaps. But Kuhn was right about this: the accumulation process generates not just something more, but often something altogether new. Sometimes the new involves the literal discovery of something which hadn’t previously been known (electrons, general relativity). At least as important, however, are conceptual novelties, changes in the ways that people understand – and often misunderstand – the material world: their operating paradigms.

Of course, the fundamental laws and processes of the natural world exist independently of human paradigms: the Earth orbited the Sun regardless of whether people signed on to a Ptolemaic or a Copernican perspective. So far as we know, light travelled at the same speed during the age of dinosaurs as it does today, just as special and general relativity were valid before being identified by Albert Einstein. Our insights, however, are always ‘evolving’. This sort of change is both frightening and exciting. After all, it’s hard to give up a cherished idea, particularly one that took a while to catch on but that eventually becomes widely accepted. And for many people – scientists and non-scientists alike – it’s even harder to give up ideas that appeared to have the seal of scientific approval. Isn’t that what science is supposed to be: a series of iron-clad factual statements of what we know to be true? In fact, this is itself untrue.

Science is a process, which, unlike ideology, is distinguished by intellectual flexibility, by a graceful, grateful (albeit sometimes grudging) acceptance of the need to change our minds, as our understanding of the world evolves. Most people aren't revolutionaries, scientific or otherwise. But anyone aspiring to be well-informed needs to understand not only the most important scientific findings, but also their provisional nature, and the need to avoid hardening of the categories: to know when it is time to lose an existing paradigm and replace it with a new one. What is more, they need to see this transition as progress rather than a sign of weakness, which is more difficult than one might think. A good paradigm is a tough thing to lose. There is a long list of ideas that were considered 'scientifically valid' in their day and have since been discarded. Belief in a flat Earth is a prominent one. Other lost theories include the ether, long believed to constitute a substance that propagates light waves, and whose explanatory reach was later extended to include electromagnetic radiation generally; or 'caloric', a hypothetical substance that ostensibly embodied heat energy, and which flowed from hotter bodies to colder ones. Nor are paradigm shifts confined to the distant scientific past. Some of the most dramatic paradigm shifts have involved bio-medicine: no wonder that much of the complaint about science being fickle comes from a confusion at changing advice about our bodies and how to care for them. Thanks to Louis Pasteur, Robert Koch, Joseph Lister and other pioneering 19th- and 20th-century microbiologists, we came to understand the role of pathogens in causing disease, resulting in the scientific discovery that 'germs are bad'. More recently, just as people have finally adjusted to worrying about creatures so small that they can't be seen, a new generation of microbiologists have demonstrated the stunning fact that most microbes who associate with us aren't merely benign but essential for health. Nerve cells, we were long told, didn't regenerate, especially not within the brain. Now we know that actually they do. Brains can even produce whole new neurons; you can teach old dogs new tricks. Biologists have long known that life is fragile and can exist only under very special circumstances. But living organisms have recently been found thriving in some of the most challenging environments previously thought to be lifeless. Individual lives are indeed fragile, but life is remarkably robust.

Deprived of previous paradigms, many of them comforting, what's left? The loss of any paradigm is disorienting, and to be deprived of many can be downright disheartening. Perhaps we mourn the loss of certainty, of the sort that most religions offer to their followers. Perhaps it's more a search for authority, of the sort once provided by our parents. Or a universal yearning for any reliable port – even if conceptual rather than maritime – in the storms of life's unknowns. Whatever the underlying cause, people have difficulty accepting the unstable, shifting, impermanent reality of how the world is put together. And this difficulty, in turn, renders us uncomfortable with precisely the only stability and certainty that science offers: that paradigms come and go. Even more worrying, changes in scientific insights have also provided opportunities for malefactors to sow undeserved doubt. One possible corrective might be to modify the way we teach science. Currently, our insights are communicated as a catalogue of Things We Know, which has the dual disadvantage of not only making science seem a laborious exercise in memorisation, but also giving the false impression that our knowledge is petrified and immutable. Maybe, instead, we should teach science as an exciting examination of Things We Don't Yet Know. Denied the comforting blanket of illusory permanence and absolute truth, we have the opportunity and obligation to do something extraordinary: to see the world as it is, and to understand and appreciate that our images will keep changing, not because they are fundamentally flawed, but because we keep providing ourselves with better lenses. Our reality hasn't become unstable; it's just that our understanding of reality is of necessity a work in progress.

The loss of paradigms might be painful, but it is testimony to the vibrancy of science, and to the unstoppable enhancement of human understanding as we approach an increasingly accurate grasp of how our world works. According to the Bible, having eaten forbidden fruit from the Tree of Knowledge of Good and Evil, we were punished for our disobedience. As we pursue knowledge – not of good and evil, but (as Shakespeare put it) of how the world wags – we too must absorb a kind of punishment. Fortunately, losing a paradigm is less devastating than being kicked out of paradise. Moreover science doesn't need any special justification beyond the satisfaction it provides as well as the practical insights it yields. Every paradigm lost is compensated by wisdom found. I recently heard a man interviewed on my local radio station complain about the difficulty of keeping up with what he called the 'swerves of scientific wisdom': 'I spent two tours in Iraq as a gunner,' he said, 'and I know how hard it is to hit a moving target. I wish these scientific experts would just hold still.'But that's the thing. Holding still is exactly what science won't do.

Adapted from Aeon

Exercise III.

Fill in the gaps.

1) The man said he ________________ signed a contract with another man to launder money.

2) ______________ corruption will overpower any effect that paper institutions might have.

3) It was unwelcome news, allayed only by the near certainty that, in fact, Laird's ____________ was more tactical than factual.

4) It is extraordinary how you can so skillfully _____________ women from responsibility.

5) Similar statistical errors plague other ______________ studies, the researchers say.

6) The company has grown at an ________________ rate, first in Taiwan and later in China.

7) At the same time, the intensity and frequency of it will ________________ over time.

8) It's not going to _________________ me or knock my confidence.

9) I know that life is ________________ and seven days from now this will not matter.

10) Suspicion turns this way and that, but the facts don't seem to point to a single ______________.

Exercise IV.

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

ebb and flow, to give up ideas, to sound smug, to take pictures of , to synthesise complex chemicals, to peer into the workings of DNA, the most immediate threat to, the paradoxical downsides of, to face a crisis the anti-vaccination movement, in some cases

Exercise V.

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

smug	make (someone) lose courage or confidence
disavowal	changing frequently, esp. as regards one's loyalties, interests, or affection
absolve	gentle; kindly
measles	a persistent feeling of ill will or resentment resulting from a past insult or injury
immense	become converted into stone or a stony substance in such a way
fickle	extremely large or great, esp. in scale or degree
benign	an infectious viral disease causing fever and a red rash on the skin, typically occurring in childhood
petrified	set or declare (someone) free from blame, guilt, or responsibility
to grudge	having or showing an excessive pride in oneself or one's achievements
unnerved	denial of any responsibility or support for some-

	thing; repudiation

Exercise VI.

Identify the part of speech the words belong to. unwittingly, legitimacy, comparable, liable, impermanent, malefactor, laborious, justification, endeavor, rampant

Exercise VII.

Match the words to make word combinations:

nuclear	sphere
alternative	deniers
research	prospects
lingering	facts
CO2-emitting	weapons
climate-change	medicine
economic	report
scientific	effect
religious	corporations
political	belief

Exercise VIII.

Summarize the article "Paradigms lost"

4. The Trouble with Theories of Everything

Exercise I.

Say what Russian words help to guess the meaning of the following words: method, empirically, fundamental, mass, energy, revolution, contact, empirical, virtual, vacuum

Exercise II.

Make sure you know the following words and word combinations.

Advent, constrain, residual, ambiguous, impractical, workaround, insensitive, impurity, audacity, to subsume,

The Trouble with Theories of Everything

There is no known physics theory that is true at every scale—there may never be.

For centuries after the introduction of the scientific method, conventional wisdom held that there were theories that were absolutely true for all scales, even if we could never be empirically certain of this in advance. Newton's universal law of gravity, for example, was, after all, universal! It applied to falling apples and falling planets alike, and accounted for every significant observation made under the sun, and over it as well. With the advent of relativity, and general relativity in particular, it became clear that Newton's law of gravity was merely an approximation of a more fundamental theory. But the more fundamental theory, general relativity, was so mathematically beautiful that it seemed reasonable to assume that it codified perfectly and completely the behavior of space and time in the presence of mass and energy. The advent of quantum mechanics changed everything. When quantum mechanics is combined with relativity, it turns out, rather unexpectedly in fact, that the detailed nature of the physical laws that govern matter and energy actually depend on the physical scale at which you measure them. This led to perhaps the biggest scientific revolution in the 20th century: We know of no theory that both makes contact with the empirical world, and is absolutely and always true. Despite this, theoretical physicists have devoted considerable energy to chasing exactly this kind of theory. So, what is going on? Is a universal theory a legitimate goal, or will scientific truth always be scale-dependent? The combination of quantum mechanics and relativity implies an immediate scaling problem. Heisenberg's famous uncertainty principle, which lies at the heart of quantum mechanics, implies that on small scales, for short times, it is impossible to completely constrain the behavior of elementary particles. There is an inherent uncertainty in energy and momenta that can never be reduced. When this fact is combined with special relativity, the conclusion is that you cannot actually even constrain the number of particles present in a small volume for short times. So called "virtual particles" can pop in and out of the vacuum on timescales so short you cannot measure their presence directly. One striking effect of this is that when we measure the force between electrons, say, the actual measured charge on the electron—the thing that determines how strong the electric force is—depends on what scale you measure it at. The closer you get to the electron, the more deeply you are penetrating inside of the "cloud" of virtual particles that are surrounding the electron. Since positive virtual particles are attracted to the electron, the deeper you penetrate into the cloud, the less of the positive cloud and more of the negative charge on the electron you see. Then, when you set out to calculate the force between two particles, you need to include the effects of all possible virtual particles that could pop out of empty space during the period of measuring the force. This includes particles with arbitrarily large amounts of mass and energy, appearing for arbitrarily small amounts of time. When you include such effects, the calculated force is infinite. Richard Feynman shared the Nobel Prize for arriving at a method to consistently calculate a finite residual force after extracting a variety of otherwise ambiguous infinities. As a result, we can now compute, from fundamental principles, quantities such as the magnetic moment of the electron to 10 significant figures, comparing it with experiments at a level unachievable in any other area of science. But Feynman was ultimately disappointed with what he had accomplished, he thought that no sensible complete theory should produce infinities in the first place, and that the mathematical tricks he and others had developed were ultimately a kind of kludge.

Now, though, we understand things differently. Feynman's concerns were, in a sense, misplaced. The problem was not with the theory, but with trying to push the theory beyond the scales where it provides the correct description of nature. There is a reason that the infinities produced by virtual particles with arbitrarily large masses and energies are not physically relevant: They are based on the erroneous presumption that the theory is complete. Or, put another way, that the theory describes physics on all scales, even arbitrarily small scales of distance and time. But if we expect our theories to be complete, that means that before we can have a theory of *anything*, we would first have to have a theory of *everything*—a theory that included the effects of all elementary particles we already have discovered, plus all the particles we haven't yet discovered! That is impractical at best, and impossible at worst. Thus, theories that make sense must be insensitive, at the scales we can measure in the laboratory, to the effects of possible new physics at much smaller distance scales (or less likely, on much bigger scales). This is not just a practical workaround of a temporary problem, which we expect will go away as we move toward ever-better descriptions of nature. Since our empirical knowledge is likely to always be partially incomplete, the theories that work to explain that part of the universe we can probe will, by practical necessity, be insensitive to possible new physics at scales beyond our current reach. This applies even to the best physical theory we have in nature: quantum electrodynamics, which describes the quantum interactions between electrons and light. The reason we can, following Feynman's lead, throw away with impunity the infinities that theory produces is that they are artificial.

There is an alternative narrative to the story of scale in physical theory. Rather than legitimately separating theories into their individual domains, outside of which they are ineffective, scaling arguments have revealed hidden connections between theories, and pointed the way to new unified theories that encompass the original theories and themselves apply at a broader range of scale. For example, all of the hoopla over the past several years associated with the discovery of the Higgs particle was due to the fact that it was the last missing link in a theory that unifies quantum electrodynamics with another force, called the weak interaction. These are two of the four known forces in nature, and on the surface they appear very different. But we now understand that on very small scales, and very high energies, the two forces can be understood as different manifestations of the same underlying force, called the electroweak force.

Scale has also motivated physicists to try to unify another of nature's basic forces, the strong force, into a broader theory. The strong force, which acts on the quarks that make up protons and neutrons, resisted understanding until 1973. That year, three theorists, David Gross, Frank Wilczek, and David Politzer, demonstrated something absolutely unexpected and remarkable. They demonstrated that a candidate theory to describe this force, called quantum chromodynamics—in analogy with quantum electrodynamics—possessed a property they called "Asymptotic Freedom." Asymptotic Freedom causes the strong force between quarks to get weaker as the quarks are brought closer together. This explained not only an experimental phenomenon that had become known as "scaling"—where quarks within protons appeared to behave as if they were independent non-interacting particles at high energies and small distances—but it also offered the possibility to explain why no free quarks are observed in nature. If the strong force becomes weaker at small distances, it presumably can be strong enough at large distances to ensure that no free quarks ever escape their partners. The discovery that the strong force gets weaker at small distances, while electromagnetism, which gets united with the weak force, gets stronger at small distances, led theorists in the 1970s to propose that at sufficiently small scales, perhaps 15 orders of magnitude smaller than the size of a proton, all three forces (strong, weak, and electromagnetic) get unified together as a single force in what has become known as a Grand Unified Theory. Over the past 40 years we have been searching for direct evidence of this—in fact the Large Hadron Collider is just now searching for a whole set of new elementary particles that appear to be necessary for the scaling of the three forces to be just right. But while there is indirect evidence, no direct smoking gun has yet been found.

Naturally, efforts to unify three of the four known forces led to further efforts to incorporate the fourth force, gravity, into the mix. In order to do this, proposals have been made that gravity itself is merely an effective theory and at sufficiently small scales it gets merged with the other forces, but only if there are a host of extra spatial dimensions in nature that we do not observe. This theory, often called superstring theory, produced a great deal of excitement among theorists in the 1980s and 1990s, but to date there is not any evidence that it actually describes the universe we live in. If it does then it will possess a unique and new feature. Superstring theory may ultimately produce no infinities at all. Therefore, it has the potential to apply at all distance scales, no matter how small. For this reason it has become known to some as a "theory of everything"—though, in fact, the scale where all the exotica of the theory would actually appear is so small as to be essentially physically irrelevant as far as foreseeable experimental measurements would be concerned.

The recognition of the scale dependence of our understanding of physical reality has led us, over time, toward a proposed theory—string theory—for which this limitation vanishes. Is that effort the reflection of a misplaced audacity by theoretical physicists accustomed to success after success in understanding reality at ever-smaller scales? While we don't know the answers to that question, we should, at the very least, be skeptical. There is no example so far where an extrapolation as grand as that associated with string theory, not grounded by direct experimental or observational results, has provided a successful model of nature. In addition, the more we learn about string theory, the more complicated it appears to be, and many early expectations about its universalism may have been optimistic. At least as likely is the possibility that nature, as Feynman once speculated, could be like an onion, with a huge number of layers. As we peel back each layer we may find that our beautiful existing theories get subsumed in a new and larger framework. So there would always be new physics to discover, and there would never be a final, universal theory that applies for all scales of space and time, without modification. Which road is the real road to reality is up for grabs. If we knew the correct path to discovery, it wouldn't be discovery. I also like the possibility that there will forever be mysteries to solve. Because life without mystery can get very boring, at any scale.

Adapted from Nautilus

Exercise III.

Fill in the gaps.

1) Look at the mobile Internet from the late 90s until the ______________ of the App store.

2) The proton has an intrinsic angular__________________ or spin, just like other particles.

3) Any other consideration would be _________________ and not serve Apple's primary goals.

4) The government shouldn't ____________________ its ambition by current economic conditions.

5) The photon comes from the ___________________ thermal radiation which surrounds the cavity.

6) The issue is left deliberately __________________ by the writers during most of the show.

7) Light interacts with an _______________ in the diamond to produce the unusual color.

8) It is called the ___________________ and its strength is determined by three parameters, the Fermi constant being one of them.

9) This approach is based on _________________, which allows perturbation theory to be used accurately in experiments performed at very high energies.

10) There are 3,500 places in university-owned accommodation _________________ each year.

Exercise IV.

Make up sentences of your own with the following word combinations: up for grabs, at every scale, after the introduction of the scientific method, true for all scales, in advance, observation made under the sun, at the heart of, on small scales, for short times, to pop in and out of the vacuum on timescales

Exercise V.

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

empirical	based on or characterized by the methods and principles of science

theory	based on, concerned with, or verifiable by observation or experience rather than theory or pure logic
mass	a supposition or a system of ideas intended to explain something, esp. one based on general principles independent of the thing to be explained
energy	the quantity of motion of a moving body, measured as a product of its mass and velocity
revolution	based on random choice or personal whim, rather than any reason or system
space	a forcible overthrow of a government or social order in favor of a new system
momentum	the strength and vitality required for sustained physical or mental activity
arbitrary	a large amount of material
scientific	an empty area left between one-, two-, or three-dimensional points or objects

Exercise VI.

Identify the part of speech the words belong to: introduction, conventional, wisdom, empirically, universal, significant, observation, approximation, beautiful, reasonable

Exercise VII.

Match the words to make word combinations:

short	principle
uncertainty	wisdom
electroweak	world
Asymptotic	laws
legitimate	interaction
empirical	goal
physical	freedom
conventional	method
scientific	tricks
mathematical	times

Exercise VIII.

Summarize the article “The Trouble with Theories of Everything”

SUPPLEMENTARY READING

Kilogram Redefined

On the morning of Friday, November 16, scientists and diplomats crammed into an auditorium in Versailles, a stone's throw from the Sun King's gilded chateau. Patrick Abbott, an American physicist, had flown into France for the long weekend. Forehead gleaming and blue suit jacket draped across his lap, Abbott watched from a packed balcony as a group of diplomats from 60 different countries voted unanimously on a treaty that intended to change global trade and technology forever.

The vote re-defined the metric system for the first time since 1983. The new system completely upends the historical methods for setting standards using physical objects. Previous systems have used things like the notches on a metal rod to set a distance standard. Up until the vote, the kilogram had been based on a platinum-iridium cylinder stored under lock and key in France.

Scientists have now scrapped all physical objects from the system. The units are instead based on fundamental constants of nature. For example, the meter has been defined in terms of the speed of light. This means that as long as you can measure the speed of light, you can create a meter stick; you don't need access to a special object. Using this principle, astronauts on Mars could theoretically make a precise tape measure from scratch.

These standards offer more stability because fundamental constants don't change over time. In the 1960s, for example, a more precise standard for time made possible GPS technology, which needed to keep time to one-billionth of a second per day. With more precise standards for the kilogram, mole, Kelvin, and Ampere, scientists anticipate more technology breakthroughs. "This [is] the biggest revolution in measurement since the French revolution," said Bill Phillips, a physics Nobel Laureate, from the stage below. Perhaps the biggest change was in the definition of the kilogram, which was the last remaining unit to be based on a physical artifact: the International Prototype Kilogram, also known as Le Grand K, locked in a vault in a Paris suburb. While scientists will still monitor and study Le Grand K, it no longer has its former scientific significance. Now, it's just a cylinder with a lot of history. Starting in May, the kilogram will be defined in terms of Planck's constant, a number that relates a radio wave's energy to its frequency.

The system was due for an upgrade, says Abbott. The French cylinder tends to gain weight over time. But still, he's got a soft spot for it. "There are a lot of people who refer to the International Prototype Kilogram irreverently as a hunk of metal. They'll say how outrageous it is for us to still use it in the 21st century," says Abbott. "But the fact remains that it's done a wonderful job for over a century. Yes, it has changed from its original value. But has it been a problem? No. I get kind of defensive about it."

And so he should. He's allowed a little sentimentality: Abbott, who works at the National Institute of Standards and Technology, is one of three designated keepers of the US kilogram standard. The lab maintains the standard using a collection of platinum-iridium cylinders stored in an underground lab in Maryland, all replicas of the IPK. All scales manufactured in the US have to be calibrated using some method that traces back to these weights. Your bathroom scale was calibrated by a weight whose mass was confirmed via another weight, and so on, where the last weight in the calibration chain is perching in a bell jar in Abbott's lab.

A month ago at his lab in Maryland, Abbott showed me the weights. He handled the weights sweetly, almost like an owner tending to his pets. The first time he ever picked up one of the kilogram replicas, to place it inside a machine, was 12 years ago. The proper protocol involves grabbing them with a pair of tongs covered in soft chamois leather and coated in lint paper. "I was so scared," he says. "It was like if someone had said, 'Why don't you take my Ferrari for a ride?'" The IPK's home lab in France sells kilogram cylinders at around $85,000 apiece, depending on the price of platinum. Platinum iridium is an extremely hard material and difficult to scratch, but "it makes you paranoid," he says.

Abbott also has to monitor the weights, to check that their masses stay the same over time. In the lab, he has developed a nearly obsessive attention to cleanliness and frequently reminds his colleagues to change their gloves. "If your gloves are dirty, and you pick up a tool, whatever's on the gloves are going to go on the tool. And that means it could get on the mass and change its weight," he says. "You have to remember where your hands have been, and what they've touched." His vigilance has kept the cylinders largely safe from mishaps. "One time I dropped one of the masses rather hard [inside a machine], and it fell over," says Abbott. "I was worried about that, but it didn't hurt anything."

He knows the weights well enough to have favorites: K4 and K79, whose numbers signify the order in which they were manufactured. "They're just so stable over the years, so I really like them," he says. "When you measure their mass, they really don't change."

K4, along with another cylinder named K20, are the most historic items in the collection: both are 130-year-old platinum iridium cylinders that are replicas of Le Grand K. "They're brothers, cut from the same bar of platinum iridium," says Abbott. Periodically, he or one of his colleagues have to hand-carry them to France, to check if their masses have fluctuated against the one true kilogram. There, they reunite the cylinders, one per trip, with its brother at its home French lab, which compares their weights.

Abbott has made the trip once, in 2011. "It's a real cloak-and-dagger affair," he says. He treated the kilogram like a precious carry-on. Using the tongs, he placed it in a custom-built container, a tiny covered platform with ungreased screws that squeak when you fiddle with them. Then he wrapped it in bubble paper and stuck it inside a camera bag. To keep customs and TSA officials' grubby hands from opening the container, the director of NIST wrote him an official letter describing the mission to accompany the kilogram.

On the plane, Abbott kept the kilogram next to him on the seat for the whole ride. He even took it to the bathroom with him. “I didn’t want to be the one known for losing the kilogram,” says Abbott.

In the end, it was a meeting in Versailles that concluded the cylinders’ travels. Abbott’s day-to-day work won’t change too much once the kilogram gets its new definition in May. He’ll continue to monitor his weights—they’re still a practical way of calibrating other weights. The key difference is that they no longer have to trek back to France. The cylinder won’t need to go on any bathroom trips. Instead, Abbott and his colleagues will check the mass of the cylinders using a new machine called the Kibble balance.

When you place a weight on the Kibble balance, the machine produces an electric current proportional to Planck’s constant. With Planck’s constant set, the kilogram will correspond to a specific amount of current in the Kibble balance. The promise in this design is that even if the balance breaks, they can just fix it—something that you can’t do if you dent a platinum-iridium cylinder.

The keepers of the Kibble balance are now the new caretakers of the mass standard. And they are just as obsessive as Abbott. They’ve hooked up various parts of the machine to the Internet. When the machine is collecting data, Darine El Haddad, a physicist at NIST, regularly logs in from home to see how it’s doing.

Many of Haddad’s Kibble balance colleagues have even gotten tattoos of Planck’s constant on their forearms. Haddad, on the other hand, showed up to Versailles with merely a week-old henna graphic on her forearm, soon to fade. “I’m very committed to Planck’s constant,” assures Haddad. “I just haven’t committed to a tattoo yet.”

Adapted from Wired Magazine

Life on Mars

In a white dome on a bare mountain, six of us are road-testing life in a Martian colony. This is what I’ve learned so far

I don’t quite remember what it’s like to wake up on Earth. Five months after ‘landing on Mars’, my day begins in a white dome in the middle of a red lava field, and I wonder: do we have enough power to turn on the heat? Will the weather let us suit up and check the greenhouses? Are my air fans going to work?

These thoughts circle in my brain as I pad downstairs for that first cup of something warm. The news that awaits me there will be in watts, percentage humidity and degrees Celsius, telling me what happened in and around our habitat overnight, and how much power we’re likely to have for the rest of today. I will hear water churning in the hydroponic systems, along with the hum of the lurid pink growing lights in the biology lab. I will see the same crewmates, kitchen and two-foot round porthole I’ve seen every morning for five months. That view of the jagged rocks beyond is a constant reminder that our world – this world we’re sharing for one year as a test run for life on Mars – is hostile and mysterious.

Let’s be clear: simulated Mars (or sMars) is technically your world. The six of us landed on the big island of Hawaii in late August 2015. A few days of training later – this is how you use the power systems, that is the right way to tap on the water tank, here is how to get into a spacesuit without dislocating anything – the door to the airlock shut, and we were ‘off planet’ for a year and a day, camped on the slopes of Mauna Kea. As simulated astronauts, we are a deliberately diverse crew: a space architect, an engineer, three scientists and a crew doctor (me). When we emerge on 28 August 2016, we’ll be veterans of the longest NASA-funded Mars simulation in history.

At first, our mission garnered only modest attention. Then The Martian was released, and all heck broke loose on sMars. The media came calling, only to be stymied by our mission’s inability to use a telephone. For this entire year, we are on a 20-minute communication delay, which applies in each direction, reflecting the maximum light-time travel between Mars and Earth – essentially, how long it takes a message from one planet to reach the other when the two are as far apart as they can be. For good and ill, we can’t take calls or have Skype interviews; we can’t do live media appearances; can’t be filmed, photographed or recorded in any way, except by ourselves.

Not only is the light-time delay an effective filter, it is also a critical part of the psychological construct that keeps us, and everyone back on Earth, behaving as though the six of us really are on Mars. Simulating the time gap created by millions of miles of space allows researchers to study how communication works, or doesn’t, when every message between the crew and mission control takes 40 minutes for a response. Think about how a delay like that affects the classic space-movie scenario: ‘Houston, we have a problem, and.... we’ll hear back from you about it in three-quarters of an hour.’

Though it spares us certain headaches, the light-time delay makes life here more precarious than it would be otherwise. The 20-minute communication gaps might be technically artificial, but in many ways they are as real to us as the dome we live under. Take the way we’d deal with medical disasters. Unlike in deep space, on sMars, I can dial 911. Even so, it will be hours before we get a response. So, what happens in a medical disaster? It’s on me, the space doc, to fix it, if possible.

The same goes for engineering problems. We’ve had water leaks in the airlock; as they are wont to do anywhere in the known Universe, appliances have self-destructed; and our hydrogen fuel cells have never worked quite right. For such issues, the chief engineer and crew take care of it, if we can. For food and water, we get periodic supply drops. In between, we subsist on what we have, just as the eventual Mars crews will, and we do our best to live within our limits.

That needful sense of independence from Earth – and interdependence on each other – is the huge upside to the long, dark, 20-minute delay. Plus, without a phone or internet to distract us, we get lots of work done. Also, without those familiar lines of connection, it’s almost like we’re alone together on another planet – which, when you live in a dome at 8,000 feet above sea level on the barren side of a volcano, is sort of the idea.

We’ve learned to repair, repurpose and rebuild things we never would have otherwise. For months, a blue latex tourniquet has been holding parts of my electricity-producing bicycle’s motor in place. We’ve learned that a two-gallon plastic pretzel jar is perfect for growing certain species of bacteria, as well as for filtering water through volcanic rock. On sMars, where there is neither money nor anywhere to spend it, value is based almost solely on usefulness: of an object, a task, even a person.

Life on sMars, like on Mars itself, is elemental. Our chief concerns revolve around sun, air, water and rock – specifically, what we can and can’t do with those four basics in the right combinations. The Sun creates our energy. We, in turn, transform that energy into artificial light, in colours of the spectrum that most please our plants. The plants take up water, and set their roots in rocks that we’ve gathered from the surface. Their stems reach up towards the light, and our hopes grow with them: exhaled by the green leaves, born in the flowers that will bloom into fruit.

All of that has to take place inside our dome – an analogue of what life on Mars might be one day. The analogue is necessarily imperfect. On real Mars, the air is extremely thin and composed mostly of carbon dioxide. Because it is not shielded by big radiation belts like Earth’s, Mars’s atmosphere is constantly being blown away by the Sun. According to MAVEN, a Mars-orbiting satellite built by NASA, the solar wind is stripping away 9.6 tons of atmosphere a day. To make matters worse, the surface of Mars is being irradiated in a way that Earth has probably never had to deal with – not since life began, anyway. Here on sMars, we fare far better: we have breathable air at a comfortable temperature and pressure, held by full Earth gravity. We have comfy, natural radiation shielding, and regular robotic supplies of food and water. Not frequent, mind you, but often enough to keep us going.

In between visits from the robots, we make the most of the resources we find. When conditions are right, we can pull water from the ground using small plastic tents. Future Mars crews will have to figure out some equivalent way to access their own local water source. We brought along seeds, soil, and a special kind of bacteria. Cyanobacteria, as the name suggests, are green. In the bottle, they look thin and luminescent, like jello before it congeals. These versatile little creatures can convert carbon dioxide into breathable air. They can purify water. They can feed off the sparse Martian menu, using nitrogen from the air and minerals from the ground, or they can consume urine and break down our waste. Purely by living, breathing, eating and excreting, these little bacteria turn soil that’s been dried and fried under the pink Martian sky into a useful growing medium, and in the process make everything from biofuel to proteins – proteins by the ton, potentially – for future Martian colonists.

Wait, you say: you’re eating green bacteria? The answer is not yet, but if our French astrobiologist placed a bowl of them before me, I’d try them. When every morsel of food in storage is some shade of just-add-water, anything fresh – even bacteria – becomes vastly more appealing, not just for taste but for health reasons.

We need to eat living things to continue living ourselves. So we operate like a collective of scientist-farmers, each taken to growing or culturing something: herbs, sweet peas, grass (surprisingly tasty), tomatoes, bread, yoghurt. Without our crops and cultures, healthy food would be on the endangered list, and so would we.

Collaboration is one of the key motivations behind the sMars project: to find out what people need to live, work and survive together on other planets, and how to give it to them. The idea sounds simple in principle, but is difficult in practice. To work together effectively, people need more than just food, water and energy. Shared mission goals help, but they still aren't enough to keep people happy for months on end. So what is enough? The belief – the hope – is that there's a recipe for making it work: that the right people, given the right tools, can live together in a small space under stressful circumstances for years and continue to perform at near-peak levels, the way that astronauts do when in low-Earth orbit aboard the International Space Station. Our jobs as simulated astronauts is to test out potential ingredients for that recipe.

What this means is that life up here is eclectic, experimental, and occasionally unpredictable. There are scheduled tasks, unscheduled time for play and rest, experimental communication methods, virtual-reality trips to beaches and forests on Earth, and a lot of negotiation among the crew. Moving into the dome is a bit like suddenly having five spouses. You rapidly discover that what's clean, polite, or acceptable to you won't necessarily be clean, polite, or acceptable to someone else. Since we're all here for the long haul – breaking up is not an option during a space mission – we've each had to adapt in five different directions at once as quickly as possible, while also doing our jobs.

Learning how to do that has been the most challenging part of the adventure. On the surface, it's straightforward. I'm the space doctor. I keep everyone healthy while we run through the physical, psychological and emotional mazes before us. That sounds pretty futuristic, and it is, sort of. But without a hospital, pharmacy or medical laboratory, space medicine turns out to be pretty old-school. Healthcare on sMars resembles the time when doctors were trained scholars with some tools and a few supplies who made house calls.

Space medicine, as it will be practised on Mars and beyond, is a trip into the unknown. Not only can't you take all the machinery, drugs and tests with you, but when you have six people in a habitat the size of a modest apartment, you have to quickly make some unorthodox choices. For example, where to treat people when every square inch is either reserved for science or functionally used as common workspace? I keep the bulk of my supplies in the biology lab, but there is no privacy there for an exam. So, like my father, a psychiatrist who maintained a home office, I treat people in my crew quarters. My room, at least, has a place to lie people flat, and a door that closes so we can chat freely about whatever ails them, be it mental or physical.

Turning my quarters into a doctor's office solved one issue, but many more aren't so easy. I am most troubled by my limited treatment options. Again, I fall back on the past to make a go of it in the present, and look for something I can dispense in lieu of pills, powders and poultices. In the places of those scarce or non-existent resources, I offer something I have in abundance: my medical insights about what they're experiencing, why, and how to manage it until it heals itself. This mode of operation can sometimes leave me feeling inadequate. Then, I remember: since before the dawn of civilisation, healers in all societies have fallen back on these same techniques.

Maybe here, at civilisation's edge, is as good a place as any to go back to the traditional regimen of sitting, listening, asking and explaining. Maybe I can't write a prescription and make it all go away but, for once, I'm not expected to. There's no line of patients waiting to see me. I have all the time in the world. I only had to leave the planet to get it. In that way, sMars is sort of a dream come true. In several other ways – the minimal medicines, tests, and treatments among them – it's a daily nightmare.

In this white dome on this red planet we all come face to face with what we love, what we lack, what we need to live, and what we fear the most. I'm a skydiving, worlds-travelling, motorcycle-riding doctor. I'm not accustomed to needing much or fearing much. After college, I bummed across Australia with only a backpack. I camped on a beach for more than a week, living off beans and what I found in the bush, and was fine. Even as a kid, I was afraid of just one thing: Jupiter. I had a recurring dream that I was flying toward that gas giant, skimming over the fractured ice surfaces of Europa and Ganymede. Closing in on Io, with its spotted mask of volcanoes, I would think: 'Too close! Too close!' and wake up. Those were the only nightmares I ever had until medical school, when, napping on a cot in some dark corner, my fear of a giant planet morphed into a terror of missing hospital pages. I would wake with a start, convinced that I'd slept through a call to a bedside consultation, an emergency surgery, or my last chance to say goodbye to a patient.

On sMars, I have a new fear as a constant companion. My worry about this mission, and about any space venture, is that the emergency call will come and I'll be right there, but totally unable to help. There will be no ventilators, no ICUs and no blood transfusions, unless we staff the mission only with type-O astronauts (not a bad idea). Thankfully, I haven't had to find out yet. The only surgery I've done so far is wart-removal. As much as I enjoy suiting up and going in with a syringe of anaesthetic and a scalpel, I'll be happy if my Martian edge-wielding ends at that big toe. That's another strange thing about space: what would have been a boring day at the office back on Earth is almost too much excitement. On Earth, heart attacks and strokes are routine parts of a day's work. Here, life is so precious and precarious to begin with that having to stitch up a crewmate after a fall on the rocks is a high-level manoeuvre.

Nothing I've ever done – not even night shifts in ER – has drawn more attention to the frailty of the human form than donning a space suit. On sMars, you have to suit up every time you leave, just as humans will when we get to Mars. A space suit is an entire ecosystem that follows you around, feeding and watering and warming you. It marks you as a tenderfoot from a gentle world. You are wrapped and padded to the point where you can visit places where our form of life was never designed to go and return in one piece.

Five months into our expedition, we are missing parts of the terrestrial environment we used to take for granted. Replicating the Martian experience means no direct sunlight or wind on our faces for an entire year. No rainfall, either. Even those of us from Southern California are used to seeing rain once in a while. Water falling from the sky – the sky! – hasn't happened on Mars in… hundreds of millions of years. In the future we're trying to build, we will have to learn how not to fear the various deprivations. We'll have to learn to embrace them instead, beginning with our own, very real, human limitations.

It is a given that the success of a future Mars colony will depend on developing the right technology, but a crucial lesson from sMars is that technology is the lowest common denominator. Mechanical solutions for getting a crew there and back alive will take shape as time and money allow. What cannot be engineered is people. Physically and mentally, emotionally and spiritually, we are the black boxes in this white dome bound for the red planet.

Physiology is tough to outwit, though we're making some progress. With artificial gravity and good radiation shielding, we might dodge some of the worst of what happens to the body in space. What will then remain, standing between us and our goal of becoming an interplanetary species? The same forces that drive our most basic behaviour on this planet: individual psychology and group dynamics. How we get along with each other (and with ourselves) is what allows our exploratory missions to succeed, or what dooms them to failure. Unlike temperature, humidity and power supply, mental states cannot be fully accounted for beforehand. Or can they? What if there is some secret to living in harmony that we can discover by practising beforehand on sMars?

This is what the six of us came here for: to get along and, in the process, help press humanity outward into the Universe. To hasten the day when people put boots on Mars, and probe its surface for signs of past or present life. In the meanwhile on this barren hillside, we are also finding something of our essential natures. True, whenever we venture into the wilderness, we confront the limits of self-sufficiency and a heightened dependence on those around us. Also true: most of us never experience anything more intense than a camping trip, where you can only get so lost before you run into civilisation again, or it comes looking for you. On Mars and beyond, the experience will be taken to a new level. Ponder this: how would it change your worldview if every person you laid eyes on for years was utterly necessary for your survival? That's life on sMars, and that will be life on real Mars: distant and inhospitable, populated entirely by people you cannot live without, and who cannot live without you.

I imagined many things about this trip. I practised for a long time to go to Mars. It turns out that Mars is just a place on whose surface rests a dome. The dome itself is just a fancy box. With the hatch closed, the world contracts not into 1,200 square feet of storage, scientific equipment and medical supplies, but into six human bodies. We form a single unit, unmappable but not unknowable, with vast minds and complex pasts; with disparate beliefs, preferences and desires. The contents of the whole world is them – is us.

When I wake up tomorrow, the entire world will be within earshot. I've never been able to say that before. No matter where I go on Earth, I'll never be able to say it again.

Adapted from Aeon

What Will We Wear on Mars?

Elon Musk and President Trump are both determined to send humans to Mars. But do we have the spacesuits to get us there?

As far as vacation spots go, Mars wouldn't be on the top of many people's lists. Sure, Olympus Mons, the tallest mountain in the solar system, might be good for a 'gram or two. But Mars, on the whole, isn't a pleasant place to hang out.

There's its inhospitable terrain, for one, which is mostly canyons, volcanoes, craters, and dry lake beds, and not much else. Mars has a thin atmosphere of mostly carbon dioxide, without an ozone-protecting magnetosphere or a charged-particle-trapping Van Allen belt to buffer its surface — and anyone on it — from cosmic rays and solar radiation. Temperatures can vary wildly too, even at the equator, swinging from 70 degrees Fahrenheit on a summer day to minus 100 degrees at night.

Plus, intrepid tourists will have to brace themselves for violent dust storms — much like the one Matt Damon struggled with at the beginning of The Martian — that can span continent-size distances and persist for weeks at a time. Then there's the question of what to wear.

Abigail Harrison thinks about this question a lot. On Earth, she likes to keep her outfits interesting — "bold, bright, and unique" — but she would trade everything in a heartbeat for a spacesuit for Mars. She's harbored the same dream since she was knee-high: Not only does Harrison want to be an astronaut, she wants to be the first astronaut to leave tracks on the red planet.

Today, Harrison's dream is closer than ever. She's finishing up her junior year at Wellesley College, where she double-majors in astrobiology and Russian. She's also deeply embedded in the space community. As "Astronaut Abby," Harrison runs The Mars Generation, an advocacy group that promotes STEM education, trains "space ambassadors," and provides scholarships toSpace Camp, a program run by the nonprofit US Space & Rocket Center in Huntsville, Alabama. More vitally for Harrison, both federal and commercial enterprises have embarked on a new "space race" that could see the first manned mission to Mars in the 2030s if you're NASA, or as early as the mid-2020s if you're SpaceX CEO Elon Musk.

Even Donald J. Trump, whose interest in space lies mostly with how militarize it, wants Americans to return to the moon and then onward to explore the red planet. "We'll be sending something very beautiful to Mars in the very near future," he said in a Cabinet meeting in March. “And we’re going to areas that nobody thought possible.” And when that happens, Harrison will need the perfect outfit.

Amy Ross, an advanced spacesuit designer at NASA’s Johnson Space Center, knows it’s only a matter of time before her services are required for a manned mission to Mars. And when that happens, she’ll be prepped and ready to go. “My job is to make sure that we have a technology that’s available,” Ross says. “So when I’m called upon to build a suit for a Mars mission, even if I don’t have the full configuration on hand, I’ll have what you need to make it.” To produce a so-called “planetary exploration suit,” NASA will have to return to the drawing board. Neither the orange launch-and-entry “pumpkin suits” that astronauts wore inside the space shuttle nor the beefier EMUs used for zero-G jaunts outside the International Space Station will cut it on the Martian frontier. The first has only limited life support; the second isn’t designed for walking.

Even the suits that Neil Armstrong and Buzz Aldrin wore on the moon will be far from adequate for extravehicular activities, or EVAs, on the Martian surface. Because Mars has twice as much ground to cover and more than double its gravity, exploration on the red planet will be more physically taxing than moonwalking. This means that the suits will have to be lighter and allow greater flexibility in the waist, knees, and ankles. “On the moon, you might have a few thousand cycles of walking needed,” Ross says. “When you go to Mars, it’s potentially millions of walking cycles that you need to design a suit for. So the kind of reliability and durability required for the suit is just impressively increased.”

A spacesuit basically functions like a wearable spaceship, providing a livable cocoon under these harsh conditions yet is durable, reliable, and flexible enough for astronauts to “science the shit”out of Mars.

“When you go and potentially consider spending 500 days on the surface of Mars, your suit needs to be kind of a tool you don’t even think about,” Ross says. “We need to make sure that astronauts can just get in that suit and do whatever they need to do for the day, whether it’s the geology, the science that they need to do, or if it’s to go change the tire of of a Mars rover.”

But textiles and coatings might behave differently on Earth than on Mars. Low pressure, solar radiation, and those aforementioned dust storms might conspire to speed up deterioration or make the materials more brittle. And although they can provide a baseline, mock environments, such as NASA’s “Mars chamber,” are no substitute for real-world testing. Which is why when the as-yet-unnamed Mars 2020 rover — the heir to Curiosity — gets to work in two years, it will carry with it a small payload of Teflon, polycarbonates, and polyurethanes. By taking readings of those samples and comparing them with results of tests performed on Earth, Ross and her team will be able to figure out how long a spacesuit will last on Mars before an astronaut has to rely on one in a life-or-death situation. “The dust environment, the chemically reactive environment, and the ultraviolet radiation environment are all things we’ll have to pay attention to,” she adds. Human bodies need to be surrounded by the right amount of atmospheric pressure to survive. Too much, like in the deepest parts of the ocean, and your organs will collapse like an empty soda can. Too little, as in the case of high altitudes or in space, and water and fluids in the body will start to boil away. To combat this problem, NASA fills its suits with pressurized gas — think human-shaped airline cabins.

The problem with this method of pressurization, according to Dava Newman, a former deputy administrator at NASA and the Apollo professor of aeronautics and astronautics at MIT, is that the suits wind up looking and feeling like rigid balloons or the Michelin Man. They encumber movement and quickly exhaust the wearer. "Astronauts who perform repair work in space find the stiffness of spacesuit gloves especially challenging," Newman wrote in the January 2012 issue of NASA's ASK magazine. "Imagine manipulating tools and small parts for hours wearing gas-filled gloves that fight against the flexing of your fingers."

Newman has created a skintight elastic suit that uses shape-memory alloys to apply mechanical pressure directly to the skin. Dubbed the Biosuit, the catsuit-like garment features a complex web of cables and coils covered by seams. When an electric current is applied, the coils contract, essentially "shrink-wrapping" its wearer with the correct amount of pressure. Cooling the coils loosens the suit's grip, making it easy to don and doff.

Newman still has kinks to work out in her suit, including how to incorporate a life support system that delivers oxygen, thermal control, and other necessities without adding too much bulk. Perhaps a modular system might in order, one that allows astronauts to carry only what they need based on their assignment. But while Ross and her department at NASA are piqued by the general concept, which would allow future space explorers to move more naturally and with fewer restraints, they prefer to stick with a known quantity — at least for now. "Pressurized suits are our primary task because they're obviously feasible; we fly them now," she says. Newman's Biosuit is a technology that's still in development. "When it's ready, if the advantages outweigh the disadvantages, then that's when we'll buy it," Ross says. That's not to say mechanical counterpressure technology is completely verboten. It just might be deployed on a smaller scale, like in gloves.

In 2007, a Pratt Institute student named Ted Southern entered NASA's Astronaut Glove Challenge as part of his MFA thesis. Working with Russian spacesuit designer Nikolay Moiseev, Southern created a glove that won him second place, as well as a contract from Houston. Now at the helm of Final Frontier Design, which he founded with NASA's $100,00 prize money, Southern says he is "tantalizingly close" to developing an EVA glove that is lighter, more supple, and less unwieldy than those currently in use. Final Frontier's design uses compressive fibers and small inflatable cushions to apply pressure across the surface of the hand. "It's a non-ideal solution and I wish there was a better way, but it's one that works today," Southern told the publication last September.

Virtually every epic space movie, from The Right Stuff to Armageddon, pivots on a single scene — you know the one. It's the trailer-shot moment where our heroes, spacesuited and booted, stride toward the camera in slow motion as the rousing score builds to a crescendo. The audience cheers, thumps their chests, even sheds a tear or two. There’s something viscerally stirring about watching astronauts answering the call to adventure — perhaps the ultimate adventure — and if you don’t feel anything you’re probably dead inside. Spacesuits look pretty cool, but … should they?

Cathleen Lewis, curator of space history at the Smithsonian National Air and Space Museum considers spacesuits works of art. From the earliest flight suits to the Mercury, Gemini, and Apollo suits to the ISS EMU, she loves them all. “They’re complex machines and works of art,” she says. “In X-rays, the interior workings of the suits look like Rube Goldberg apparatus — they’re very elaborate.” Lewis likes to remind people that Russell Colley, the man whose pressurized flight suit allowed pioneering aviator Wiley Post to reach hitherto impossible altitudes, originally studied to become a fashion designer, “so he clearly had an aesthetic eye.” (Colley later went on to design spacesuits for the Project Mercury astronauts; in his obituary in 1996, the New York Times referred to him as the “Calvin Klein of spacewear.”)

As much as spacesuits are designed to function, first and foremost, there are also plenty of design choices that can be made along the way. It’s why the suits that Russian cosmonauts wear look so different from NASA and European Space Agency suits. “Those are just aesthetic choices that the designers have made,” Lewis explains. It’s probably no coincidence that Dava Newman’s Biosuit looks like something an Avenger would wear. Aesthetics are a “critical component” for design and and engineering, Newman told Wired. “I think space exploration is the most exciting thing going on,” she said. “And heroic-looking suits might help make more of a human connection for folks.” Michael Lye, a professor of industrial design at the Rhode Island School of Design, understands better than most the push and pull between form and function. Lye and his students built a full-scale model of spacesuit that “crew members” simulating Mars missions on Earth can wear on their EVAs.

“Functionality is certainly critical, but at the same time, nothing humans do is devoid of aesthetics,” Lye says. Not to mention that long before men walked on the moon, people were exploring the stars in spandex and fishbowl helmets on the covers of pulp fiction books and magazines. “Once people see something, it becomes a way of thinking about the future, and I think aesthetics play a role in that,” Lye says. “It’s much easier to get people behind ideas they find exciting and interesting than it is if they think they’re not.” Indeed when Abigail “Astronaut Abby” Harrison tours aerospace startups like Final Frontier, the thing that strikes her most about their designs is how sleek they look, “like something you would see in a sci-fi movie or you would imagine out of a sci-fi book.” While she realizes that outward appearances aren’t traditionally valued in spacesuit design, she also thinks that aesthetics will become increasingly important when recruitment for Mars missions ramps up. “The entire world is excited about space, and so when you have these really sleek, exciting-looking spacesuits, that captures people’s imagination,” Harrison says. “It allows people to really connect with these missions on a different level, and they’ll hopefully support space exploration more and be more excited about it.” And who knows? Some day in the near future, it might even be the sight of Harrison in a spacesuit, kicking up red dust on Mars, that inspires a whole new generation to follow in her bootsteps. And by then they'll know exactly how to dress for the job they want.

Adapted from Racked

Chaos Makes the Multiverse Unnecessary

Science predicts only the predictable, ignoring most of our chaotic universe.

Scientists look around the universe and see amazing structure. There are objects and processes of fantastic complexity. Every action in our universe follows exact laws of nature that are perfectly expressed in a mathematical language. These laws of nature appear fine-tuned to bring about life, and in particular, intelligent life. What exactly are these laws of nature and how do we find them?

The universe is so structured and orderly that we compare it to the most complicated and exact contraptions of the age. In the 18th and 19th centuries, the universe was compared to a perfectly working clock or watch. Philosophers then discussed the Watchmaker. In the 20th and 21st centuries, the most complicated object is a computer. The universe is compared to a perfectly working supercomputer. Researchers ask how this computer got its programming.

How does one explain all this structure? Why do the laws seem so perfect for producing life and why are they expressed in such exact mathematical language? Is the universe really as structured as it seems? One answer to some of these questions is Platonism (or its cousin Realism). This is the belief that the laws of nature are objective and have always existed. They possess an exact ideal form that exists in Plato's realm. These laws are in perfect condition and they have formed the universe that we see around us. Not only do the laws of nature exist in this realm, but they live alongside all perfectly formed mathematics. This is supposed to help explain why the laws are written in the language of mathematics.

Platonism leaves a lot to be desired. The main problem is that Platonism is metaphysics, not science. However, even if we were to accept it as true, many questions remain. Why does this Platonic world have these laws, that bring intelligent life into the universe, rather than other laws? How was this Platonic attic set up? Why does our physical universe follow these ethereal rules? How do scientists and mathematicians get access to Plato's little treasure chest of exact ideals?

The multiverse is another answer that has recently become quite fashionable. This theory is an attempt to explain why our universe has the life-giving laws that it does. One who believes in a multiverse maintains that our universe is just one of many universes. Each universe has its own set of rules and its own possible structures that come along with those rules. Physicists who push the multiverse theory believe that the laws in each universe are somewhat arbitrary. The reason we see structures fit for life in our universe is that we happen to live in one of very few universes that have such laws. While the multiverse explains some of the structure that we see, there are questions that are left open. Rather than asking why the universe has the structure it does, we can push the question back and ask why the multiverse has the structure it does. Another problem is that while the multiverse would answer some of the questions we posed if it existed, who says it actually exists? Since most believe that we have no contact with possible other universes, the question of the existence of the multiverse is essentially metaphysics.

There is another, more interesting, explanation for the structure of the laws of nature. Rather than saying that the universe is very structured, say that the universe is mostly chaotic and for the most part lacks structure. The reason why we see the structure we do is that scientists act like a sieve and focus only on those phenomena that have structure and are predictable. They do not take into account all phenomena; rather, they select those phenomena they can deal with.

Some people say that science studies all physical phenomena. This is simply not true. Who will win the next presidential election and move into the White House is a physical question that no hard scientists would venture to give an absolute prediction. Whether or not a computer will halt for a given input can be seen as a physical question and yet we learned from Alan Turing that this question cannot be answered. Scientists have classified the general textures and heights of different types of clouds, but, in general, are not at all interested in the exact shape of a cloud. Although the shape is a physical phenomenon, scientists don't even attempt to study it. Science does not study all physical phenomena. Rather, science studies predictable physical phenomena. It is almost a tautology: science predicts predictable phenomena.

Scientists have described the criteria for which phenomena they decide to study: It is called symmetry. Symmetry is the property that despite something changing, there is some part of it that remains the same. When you say that a face has symmetry, you mean that if the left side is reflected and swapped with the right side, it will still look the same. When physicists use the word symmetry they are discussing collections of physical phenomena. A set of phenomena has symmetry if it is the same after some change. The most obvious example is symmetry of location. This means that if one performs the same experiment in two different places, the results should be the same. Symmetry of time means that the outcomes of experiments should not depend on when the experiment took place. And, there are many other types of symmetry.

The phenomena that are selected by scientists for study must have many different types of symmetry. When a physicist sees a lot of phenomena, she must first determine if these phenomena have symmetry. She performs experiments in different places and at different times. If she achieves the same results, she then studies them to find the underlying cause. In contrast, if her experiments failed to be symmetric, she would ignore them.

While scientists like Galileo and Newton recognized the symmetry in physical phenomena, the power of symmetry was first truly exploited by Albert Einstein. He postulated that the laws of physics should be the same even if the experimenter is moving close to the speed of light. With this symmetry in mind, he was able to compose the laws of special relativity. Einstein was the first to understand that symmetry was the defining characteristic of physics. Whatever has symmetry will have a law of nature. The rest is not part of science.

A little after Einstein showed the vital importance of symmetry for the scientific endeavor, Emmy Noether proved a powerful theorem that established a connection between symmetry and conservation laws. This is related to the constants of nature, which are central to modern physics. Again, if there is symmetry, then there will be conservation laws and constants. The physicist must be a sieve and study those phenomena that possess symmetry and allow those that do not possess symmetry to slip through her fingers.

There are a few problems with this explanation of the structure found in the universe. For one, it seems that phenomena that we do select and that have laws of nature are exactly the phenomena that generate all the phenomena. The laws of particle physics, gravity, and quantum theory all have symmetries and are studied by physicists. All phenomena seem to come from these theories, even those that do not seem to have symmetry. So while it is beyond science to determine who the next president will be, that phenomena will be determined by sociology, which is determined by psychology, which is determined by neural biology which depends on chemistry which depends on particle physics and quantum mechanics. Determining the winner of an election is too complicated for the scientist to deal with, but the results of the election are generated by laws of physics that are part of science.

Despite this failing of our explanation for the structure of the laws of nature, we believe it is the best candidate for being the solution. It is one of the only solutions that does not invoke any metaphysical principle or the existence of a multitude of unseen universes. We do not have to look outside the universe to find a cause for the structure that we find in the universe. Rather, we look at how we are looking at phenomena. Before we move on, we should point out that our solution has a property in common with the multiverse solution. We postulated that, for the most part, the universe is chaotic and there is not so much structure in it. We, however, focus only on the small amount of structure that there is. Similarly, one who believes in the multiverse believes that most of the multiverse lacks the structure to form intelligent life. It is only in a select few universes that we find complex structure. And we inhabitants of this complex universe are focused on that rare structure. Both solutions are about focusing on the small amount of structure in a chaotic whole.

This idea that we only see structure because we are selecting a subset of phenomena is novel and hard to wrap one's head around. There is an analogous situation in mathematics that is much easier to understand. We will focus on one important example where one can see this selection process very clearly. First we need to take a little tour of several number systems and their properties.

Consider the real numbers. In the beginning of high school, the teacher draws the real number line on the board and says that these are all the numbers one will ever need. Given two real numbers, we know how to add, subtract, multiply, and divide them. They comprise a number system that is used in every aspect of science. The real numbers also have an important property: They are totally ordered. That means that given any two different real numbers, one is less than the other. Just think of the real number line: Given any two different points on the line, one will be to the right of the other. This property is so obvious that it is barely mentioned.

While the real numbers seem like a complete picture, the story does not end there. Already in the 16th century, mathematicians started looking at more complicated number systems. They began working with an “imaginary” number i that has the property that its square is -1. This is in stark contrast to any real number whose square is never negative. They defined an imaginary number as the product of a real number and i. Mathematicians went on to define a complex number that is the sum of a real number and an imaginary number. If $r1$ and $r2$ are real numbers, then $r1+r2i$ is a complex number. Since a complex number is built from two real numbers, we usually draw all of them in a two-dimensional plane. The real number line sits in the complex plane. This corresponds to the fact that every real number, $r1$, can be seen as the complex number $r1+0i$ (that is, itself with zero complex component).

We know how to add, subtract, multiply, and divide complex numbers. However, there is one property that is different about the complex numbers. In contrast to the real numbers, the complex numbers are not totally ordered. Given two complex numbers, say $3 + 7.2i$ and $6 - 4i$, can we tell which one is more and which one is less? There is no obvious answer. (In fact, one can totally order the complex numbers but the ordering will not respect the multiplication of complex numbers.) The fact that the complex numbers are not totally ordered means that we lose structure when we go from the real numbers to the complex numbers.

The story is not over with the complex numbers. Just as one can construct the complex numbers from pairs of real numbers, so too can one construct the quaternions from pairs of complex numbers. Let $c1 = r1 + r2i$ and $c2 = r3 + r4i$ be complex numbers; then we can construct a quaternion as $q = c1 + c2j$ where j is a special number. It turns out that every quaternion can be written as

$r1 + r2i + r3j + r4k$,

where i, j, and k are all special numbers similar to complex numbers (they are defined by $ijk = -1 = i2 =j2 = k2$). So while the complex numbers are comprised of two real numbers, the quaternions are comprised of four real numbers. Every complex number $r1 + r2i$ can be seen as a special type of quaternion: $r1+ r2i + 0j + 0k$. We can think of the quaternions as a four-dimensional space that has the complex numbers as a two-dimensional subset of it. We humans have a hard time visualizing such higher-dimensional spaces.

The quaternions are a full-fledged number system. They can be added, subtracted, multiplied, and divided with ease. Like the complex numbers, they fail to be totally ordered. But they have even less structure than the complex numbers. While the multiplication of complex numbers is commutative, that is, for all complex numbers $c1$ and $c2$ we have that $c1c2 = c2c1$, this is not true for all quaternions. This means there are quaternions $q1$ and $q2$ such that $q1q2$ is different than $q2q1$.

This process of doubling a number system with a new special number is called the “Cayley–Dickson construction,” named after the mathematicians Arthur Cayley and Leonard Eugene Dickson. Given a certain type of number system, one gets another number system that is twice the dimension of the original system. The new system that one develops has less structure (i.e. fewer axioms) than the starting system.

If we apply the Cayley–Dickson construction to the quaternions, we get the number system called the octonions. This is an eight-dimensional number system. That means that each of the octonions can be written with eight real numbers as
r1+ r2i + r3j + r4k +r5l + r6m + r7n + r8p.

Although it is slightly complicated, it is known how to add, subtract, multiply, and divide octonions. Every quaternion can be written as a special type of octonion in which the last four coefficients are zero.

Like the quaternions, the octonions are neither totally ordered nor commutative. However, the octonions also fail to be associative. In detail, all the number systems that we have so far discussed possess the associative property. This means that for any three elements, a, b, and c, the two ways of multiplying them, a(bc) and (ab)c, are equal. However, the octonions fail to be associative. That is, there exists octonions o1, o2 and o3 such that o1(o2o3) ≠ (o1o2)o3.

We can go on with this doubling and get an even larger, 16-dimensional number system called the sedenions. In order to describe a sedonion, one would have to give 16 real numbers. Octonions are a special type of sedonion: their last eight coefficients are all zero. But researchers steer clear of sedenions because they lose an important property. While one can add, subtract, and multiply sedenions, there is no way to nicely divide them. Most physicists think this is beyond the pale and “just” mathematics. Even mathematicians find sedenions hard to deal with. One can go on to formulate 32-dimensional number systems and 64-dimensional number systems, and so on. But they are usually not discussed because, as of now, they do not have many applications. We will concentrate on the octonions.

Let us discuss the applicability of these number systems. The real numbers are used in every aspect of physics. All quantities, measurements, and lengths of physical objects or processes are given as real numbers. Although complex numbers were formulated by mathematicians to help solve equations (iis the solution to the equation x2 = -1), physicists started using complex numbers to discuss waves in the middle of the 19th century. In the 20th century, complex numbers became fundamental for the study of quantum mechanics. By now, the role of complex numbers is very important in many different branches of physics. The quaternions show up in physics but are not a major player. The octonions, the sedenions, and the larger number systems rarely arise in the physics literature.

The usual view of these number systems is to think that the real numbers are fundamental while the complex, quaternions, and octonions are strange larger sets that keep mathematicians and some physicists busy. The larger number systems seem unimportant and less interesting. Let us turn this view on its head. Rather than looking at the real numbers as central and the octonions as strange larger number systems, think of the octonions as fundamental and all the other number systems as just special subsets of octonions. The only number system that really exists is the octonions. To paraphrase Leopold Kronecker, “God made the octonions, all else is the work of man.” The octonions contain every number that we will ever need. (And, as we stated earlier, we can do the same trick with the sedenions and even the 64-dimensional number system. We shall fix our ideas with the octonions.)

Let us explore how we can derive all the properties of the number systems that we are familiar with. Although the multiplication in the octonions is not associative, if one wants an associative multiplication, one can look at a special subset of the octonions. (We are using the word “subset” but we need a special type of subset that respects the operations of the number system. Such subsets are called “subgroups,” “subfields,” or “sub-normed-division-algebras.”) So if one selects the subset of all octonions of the form
r1+ r2i + r3j + r4k + 0l + 0m + 0n + 0p,
then the multiplication will be associative (like the quaternions). If one further looks at all the octonions of the form
r1+ r2i + 0j + 0k + 0l + 0m + 0n + 0p,
then the multiplication will be commutative (like the complex numbers). If one further selects all the octonions of the form
r1 + 0i + 0j + 0k + 0l + 0m + 0n + 0p,
then they will have a totally ordered number system. All the axioms that one wants satisfied are found “sitting inside” the octonions.

This is not strange. Whenever we have a structure, we can focus on a subset of special elements that satisfies certain properties. Take, for example, any group. We can go through the elements of the group and pick out those X such that, for all elements Y, we have that XY = YX. This subset is a commutative (abelian) group. That is, it is a fact that in any group there is a subset that is a commutative group. We simply select those parts that satisfy the axiom and ignore (“bracket out”) those that do not. The point we are making is that if a system has a certain structure, special subsets of that system will satisfy more axioms than the starting system.

This is similar to what we are doing in physics. We do not look at all phenomena. Rather, we pick out those phenomena that satisfy the requirements of symmetry and predictability. In mathematics, we describe the subset with the axiom that describes it. In physics, we describe the selected subset of phenomena with a law of nature. Notice that the mathematics for a subset chosen to satisfy an axiom is easier than the mathematics for the whole set. This is because mathematicians work with axioms. They prove theorems and make models using axioms. When such axioms are missing, the mathematics gets more complicated or impossible.

Following our analogy, a subset of phenomena is easier to describe with a law of nature stated in mathematics. In contrast, when we look at the larger set of phenomena, it is harder to find that law of nature and the mathematics would be more complicated or impossible.

There is an important analogy between physics and mathematics. In both fields, if we do not look at the entirety of a system, but rather look at special subsets of the system, we see more structure. In physics we select certain phenomena (the ones that have a type of symmetry) and ignore the rest. In mathematics we are looking at certain subsets of structures and ignore the rest. These two bracketing operations work hand in hand.

The job of physics is to formulate a function from the collection of observed physical phenomena to mathematical structure: observed physical phenomena → mathematical structure. That is, we have to give mathematical structure to the world we observe. As physics advances and we try to understand more and more observed physical phenomena, we need larger and larger classes of mathematics. In terms of this function, if we are to enlarge the input of the function, we need to enlarge the output of the function.

There are many examples of this broadening of physics and mathematics. When physicists started working with quantum mechanics they realized that the totally ordered real numbers are too restrictive for their needs. They required a number system with fewer axioms. They found the complex numbers. When Albert Einstein wanted to describe general relativity, he realized that the mathematical structure of Euclidean space with its axiom of flatness (Euclid’s fifth axiom) was too restrictive. He needed curved, non-Euclidian space to describe the spacetime of general relativity. In quantum mechanics it is known that for some systems, if we first measure X and then Y, we will get different results than first measuring Y and then measuring X. In order to describe this situation mathematically, one needed to leave the nice world of commutativity. They required the larger class of structures where commutativity is not assumed.

When Boltzmann and Gibbs started talking about statistical mechanics, they realized that laws they were coming up with were no longer deterministic. Outcomes of experiments no longer either happen ($p(X) = 1$) or do not happen ($p(X) = 0$). Rather, with statistical mechanics one needs probability theory. The chance of a certain outcome of an experiment is a probability ($p(X)$) is an element of the infinite set $[0,1]$ rather than the restrictive finite subset $\{0,1\}$).

When scientists started talking about the logic of quantum events, they realized that the usual logic, which is distributive, is too restrictive. They needed to formulate the larger class of logics in which the distributive axiom does not necessarily hold true. This is now called quantum logic. Paul A.M. Dirac understood this loosening of axioms about 85 years ago when he wrote the following:

The steady progress of physics requires for its theoretical formulation a mathematics which get continually more advanced. This is only natural and to be expected. What however was not expected by the scientific workers of the last century was the particular form that the line of advancement of mathematics would take, namely it was expected that mathematics would get more and more complicated, but would rest on a permanent basis of axioms and definitions, while actually the modern physical developments have required a mathematics that continually shifts its foundation and gets more abstract. Non-Euclidean geometry and noncommutative algebra, which were at one time were considered to be purely fictions of the mind and pastimes of logical thinkers, have now been found to be very necessary for the description of general facts of the physical world. It seems likely that this process of increasing abstraction will continue in the future and the advance in physics is to be associated with continual modification and generalisation of the axioms at the base of mathematics rather than with a logical development of any one mathematical scheme on a fixed foundation.1

As physics progresses and we become aware of more and more physical phenomena, larger and larger classes of mathematical structures are needed and we get them by looking at fewer and fewer axioms. Dirac calls these mathematical structures with fewer axioms "increasing abstraction" and "generalisations of the axioms." There is no doubt that if Dirac lived now, he would talk about the rise of octonions and even the sedenions within the needed number systems.

In order to describe more phenomena, we will need larger and larger classes of mathematical structures and hence fewer and fewer axioms. What is the logical conclusion to this trend? How far can this go? Physics wants to describe more and more phenomena in our universe. Let us say we were interested in describing all phenomena in our universe. What type of mathematics would we need? How many axioms would be needed for mathematical structure to describe all the phenomena? Of course, it is hard to predict, but it is even harder not to speculate. One possible conclusion would be that if we look at the universe in totality and not bracket any subset of phenomena, the mathematics we would need would have no axioms at all. That is, the universe in totality is devoid of structure and needs no axioms to describe it. Total lawlessness! The mathematics are just plain sets without structure. This would finally eliminate all metaphysics when dealing with the laws of nature and mathematical structure. It is only the way we look at the universe that gives us the illusion of structure.

With this view of physics we come to even more profound questions. These are the future projects of science. If the structure that we see is illusory and comes about from the way we look at certain phenomena, then why do we see this illusion? Instead of looking at the laws of nature that are formulated by scientists, we have to look at scientists and the way they pick out (subsets of phenomena and their concomitant) laws of nature. What is it about human beings that renders us so good at being sieves? Rather than looking at the universe, we should look at the way we look at the universe.

Adapted from Nautilus

Scientists Discover Exotic New Patterns of Synchronization

In a world seemingly filled with chaos, physicists have discovered new forms of synchronization and are learning how to predict and control them.

When the incoherent claps of a crowd suddenly become a pulse, as everyone starts clapping in unison, who decided? Not you; not anyone. Crickets sing in synchrony; metronomes placed side by side sway into lockstep; some fireflies blink together in the dark. All across the United States, the power grid operates at 60 hertz, its innumerable tributaries of alternating current synchronizing of their own accord. Indeed, we live because of synchronization. Neurons in our brains fire in synchronous patterns to operate our bodies and minds, and pacemaker cells in our hearts sync up to generate the beat.

Objects with rhythms naturally synchronize. Yet the phenomenon went entirely undocumented until 1665, when the Dutch physicist and inventor Christiaan Huygens spent a few days sick in bed. A pair of new pendulum clocks — a kind of timekeeping device that Huygens invented — hung side by side on the wall. Huygens noticed that the pendulums swung exactly in unison, always lurching toward each other and then away. Perhaps pressure from the air was synchronizing their swings? He conducted various experiments. Standing a table upright between the clocks had no effect on their synchronization, for instance. But when he rehung the clocks far apart or at right angles to each other, they soon fell out of phase. Huygens eventually inferred that the clocks' "sympathy," as he called it, resulted from the kicks that their swings gave each other through the wall.

When the left pendulum swings left, it kicks the wall and the other pendulum rightward, and vice versa. The clocks kick each other around until they and the wall attain their most stable, relaxed state. For the pendulums, the most stable behavior is to move in opposite directions, so that each pushes the other in the direction it's already going, the way you push a child on a swing. And this is also easiest for the wall; it no longer moves at all, because the pendulums are giving it equal and opposite kicks. Once in this self-reinforcing, synchronous state, there's no reason for the system to deviate. Many systems synchronize for similar reasons, with kicks replaced by other forms of influence.

Another Dutchman, Engelbert Kaempfer, traveled to Thailand in 1690 and observed the local fireflies flashing simultaneously "with the utmost regularity and exactness." Two centuries later, the English physicist John William Strutt (better known as Lord Rayleigh) noticed that standing two organ pipes side by side can "cause the pipes to speak in absolute unison, in spite of inevitable small differences." Radio engineers in the 1920s discovered that wiring together electrical generators with different frequencies forced them to vibrate with a common frequency — the principle behind radio communication systems.

It wasn't until 1967 that the pulsating chirps of crickets inspired the American theoretical biologist Art Winfree to propose a mathematical model of synchronization. Winfree's equation was too difficult to solve, but in 1974, a Japanese physicist named Yoshiki Kuramoto saw how to simplify the math. Kuramoto's model described a population of oscillators (things with rhythms, like metronomes and heartbeats) and showed why coupled oscillators spontaneously synchronize. Kuramoto, then 34, had little prior experience in nonlinear dynamics, the study of the feedback loops that tangle together variables in the world. When he showed his model to experts in the discipline, they failed to grasp its significance. Discouraged, he set the work aside.

Five years later, Winfree came across a précis of a talk Kuramoto had given about his model and realized that it offered a revolutionary new understanding of a subtle phenomenon that pervades the world. Kuramoto's math has proved versatile and extendable enough to account for synchronization in clusters of neurons, fireflies, pacemaker cells, starlings in flight, reacting chemicals, alternating currents and myriad other real-world populations of coupled "oscillators." "I didn't imagine at all that my model would have a wide applicability," said Kuramoto, now 78, by email. But, as ubiquitous as Kuramoto's model became, any illusions physicists had of understanding synchronization shattered in 2001. Once again, Kuramoto was at the center of the action.

In Kuramoto's original model, an oscillator can be pictured as an arrow that rotates in a circle at some natural frequency. (If it's a firefly, it might flash every time the arrow points up.) When a pair of arrows are coupled, the strength of their mutual influence depends on the sine of the angle between their pointing directions. The bigger this angle, the bigger the sine, and therefore the stronger their mutual influence. Only when the arrows point in parallel directions, and rotate together, do they stop pulling on each other. Thus, the arrows will drift until they find this state of synchrony. Even oscillators that have different natural frequencies, when coupled, reach a compromise and oscillate in tandem.

But that basic picture only explains the onset of global synchronization, where a population of oscillators all do the same thing. As well as being the simplest kind of sync, "there are plenty of examples of global synchronization; that's why people paid so much attention to that," said Adilson Motter, a physicist at Northwestern University in Chicago, and a leading sync scientist. "But in 2001, Kuramoto discovered something very different. And that's where the story of different states starts."

It was Kuramoto's Mongolian post-doc, Dorjsuren Battogtokh, who first noticed a new kind of synchronous behavior in a computer-simulated population of coupled oscillators. The identical oscillators, which were all identically coupled to their neighbors, had somehow split into two factions: Some oscillated in sync, while the rest drifted incoherently. Kuramoto presented his and Battogtokh's discovery at a 2001 meeting in Bristol, but the result didn't register in the community until Steven Strogatz, a mathematician at Cornell University, came across it in the conference proceedings two years later. "When I came to understand what I was seeing in the graphics, I didn't really believe it," Strogatz said. "What was so weird," he explained, "was that the universe looks the same from every place" in the system. And yet the oscillators responded differently to identical conditions, some ganging together while the rest went their own way, as if not coupled to anything at all. The symmetry of the system "was broken," Strogatz said, in a way that "had never been seen before."

Strogatz and his graduate student Daniel Abrams, who now studies synchronization as a professor at Northwestern, reproduced the peculiar mix of synchrony and asynchrony in computer simulations of their own and explored the conditions under which it arises. Strogatz dubbed it the "chimera" state after a mythological fire-breathing monster made of incongruous parts. (Months earlier, Strogatz had written a popular book called Sync, about the pervasiveness of global synchronization.)

Two independent teams realized this chimera state in the lab in 2012, working in different physical systems, and more experiments have seen it since. Many researchers suspect chimeras arise naturally. The brain itself seems to be a complicated kind of chimera, in that it simultaneously sustains both synchronous and asynchronous firing of neurons. Last year, researchers found qualitative similarities between the destabilization of chimera states and epileptic seizures. “We believe that further detailed studies may open new therapeutic methods for promoting seizure prediction and termination,” said co-author Iryna Omelchenko of the University of Berlin.

But the chimera state is still not fully understood. Kuramoto worked out the math verifying that the state is self-consistent, and therefore possible, but that doesn’t explain why it arises. Strogatz and Abrams further developed the math, but other researchers want “a more seat-of-the-pants, physical explanation,” Strogatz said, adding, “I think it’s fair to say that we haven’t really hit the nail on the head yet” about why the chimera state occurs. The discovery of chimeras ushered in a new era in sync science, revealing the conceivably countless exotic forms that synchronization can take. Now, theorists are working to pin down the rules for when and why the different patterns occur. These researchers have bold hopes of learning how to predict and control synchronization in many real-world contexts.

Motter and his team are finding rules about how to stabilize the synchronization of power grids and more stably integrate the U.S. grid with intermittent energy sources like solar and wind. Other researchers are looking for ways of nudging systems between different synchronous states, which could be useful for correcting irregular heartbeats. Novel forms of sync could have applications in encryption. Scientists speculate that brain function and even consciousness can be understood as a complicated and delicate balance of synchrony and asynchrony. “There’s a lot of new vibrancy to thinking about sync,” said Raissa D’Souza, a professor of computer science and mechanical engineering at University of California, Davis. “We’re gaining the tools to look at these exotic, intricate patterns beyond just simple, full synchronization or regions of synchronization and regions of randomness.”

Many of the new synchronization patterns arise in networks of oscillators, which have specific sets of connections, rather than all being coupled to one another, as assumed in the original Kuramoto model. Networks are better models of many real-world systems, like brains and the internet.

In a seminal paper in 2014, Louis Pecora of the United States Naval Research Laboratory and his co-authors put the pieces together about how to understand synchronization in networks. Building on previous work, they showed that networks break up into “clusters” of oscillators that synchronize. A special case of cluster sync is “remote synchronization,” in which oscillators that are not directly linked nonetheless sync up, forming a cluster, while the oscillators in between them behave differently, typically syncing up with another cluster. Remote synchronization jibes with findings about real-world networks, such as social networks. “Anecdotally it’s not your friend who influences your behavior so much as your friend’s friend,” D’Souza said. In 2017, Motter’s group discovered that oscillators can remotely synchronize even when the oscillators between them are drifting incoherently. This scenario “breeds remote synchronization with chimera states,” he said. He and his colleagues hypothesize that this state could be relevant to neuronal information processing, since synchronous firing sometimes spans large distances in the brain. The state might also suggest new forms of secure communication and encryption.

Then there’s chaotic synchronization, where oscillators that are individually unpredictable nonetheless sync up and evolve together. As theorists explore the math underpinning these exotic states, experimentalists have been devising new and better platforms for studying them. “Everyone prefers their own system,” said Matthew Matheny of the California Institute of Technology. In a paper inScience last month, Matheny, D’Souza, Michael Roukes and 12 co-authors reported a menagerie of new synchronous states in a network of “nanoelectromechanical oscillators,” or NEMs — essentially miniature electric drumheads, in this case. The researchers studied a ring of eight NEMs, where each one’s vibrations send electrical impulses to its nearest neighbors in the ring. Despite the simplicity of this eight-oscillator system, “we started seeing a lot of crazy things,” Matheny said.

The researchers documented 16 synchronous states that the system fell into under different initial settings, though many more, rare states might be possible. In many cases, NEMs decoupled from their nearest neighbors and remotely synchronized, vibrating in phase with tiny drumheads elsewhere in the ring. For example, in one pattern, two nearest neighbors oscillated together, but the next pair adopted a different phase; the third pair synced up with the first and the fourth pair with the second. They also found chimeralike states (though it’s hard to prove that such a small system is a true chimera).

Many exotic new synchronization patterns were seen in experiments with a ring of eight connected oscillators. In the “splay state” on the left, each oscillator’s phase differs by a set amount from its neighbors’. In the “traveling wave state” in the center, only arrows opposite each other on the ring stay in phase. The state on the right is a “noise-driven chimera”: Two sets of arrows are always synced across the ring, while arrows in between jump in and out of sync with their neighbors, seemingly at random. NEMs are more complicated than simple Kuramoto oscillators in that the frequency at which they oscillate affects their amplitude (roughly, their loudness). This inherent, self-referential “nonlinearity” of each NEM gives rise to complex mathematical relationships between them. For instance, the phase of one can affect the amplitude of its neighbor, which affects the phase of its next-nearest neighbor. The ring of NEMs serves as “a proxy for other things that are out in the wild,” said Strogatz. When you include a second variable, like amplitude variations, “that opens up a new zoo of phenomena.”

Roukes, who is a professor of physics, applied physics and biological engineering at Caltech, is most interested in what the ring of NEMs suggests about huge networks like the brain. “This is very, very primordial compared to the complexity of the brain,” he said. “If we already see this explosion in complexity, then it seems feasible to me that a network of 200 billion nodes and 2,000 trillion [connections] would have enough complexity to sustain consciousness.” In the quest to understand and control the way things sync up, scientists are searching for the mathematical rules dictating when different synchronization patterns occur. That major research effort is unfinished, but it’s already clear that synchronization is a direct manifestation of symmetry — and the way it breaks.

The link between synchronization and symmetry was first solidified by Pecora and co-authors in their 2014 paper on cluster synchronization. The scientists mapped the different synchronized clusters that can form in a network of oscillators to that network’s symmetries. In this context, symmetries refer to the ways a network’s oscillators can be swapped without changing the network, just as a square can be rotated 90 degrees or reflected horizontally, vertically or diagonally without changing its appearance. D’Souza, Matheny and their colleagues applied the same potent formalism in their recent studies with NEMs. Roughly speaking, the ring of eight NEMs has the symmetries of an octagon. But as the eight tiny drums vibrate and the system evolves, some of these symmetries spontaneously break; the NEMs divide into synchronous clusters that correspond to subgroups of the “symmetry group” called D8, which specifies all the ways you can rotate and reflect an octagon that leave it unchanged. When the NEMs sync up with their next-nearest neighbors, for example, alternating their pattern around the ring, D8 reduces to the subgroup D4. This means the network of NEMs can be rotated by two positions or reflected across two axes without changing the pattern.

Even chimeras can be described in the language of clusters and symmetry subgroups. “The synchronized part is one big synchronized cluster, and the desynchronized part is a bunch of single clusters,” said Joe Hart, an experimentalist at the Naval Research Lab who collaborates with Pecora and Motter. Synchronization seems to spring from symmetry, and yet scientists have also discovered that asymmetry helps stabilize synchronous states. “It is a little bit paradoxical,” Hart admitted. In February, Motter, Hart, Raj Roy of the University of Maryland and Yuanzhao Zhang of Northwestern reported in Physical Review Letters that introducing an asymmetry into a cluster actually strengthens its synchrony. For example, making the coupling between two oscillators in the cluster unidirectional instead of mutual not only doesn’t disturb the cluster’s synchrony, it actually makes its state more robust to noise and perturbations from elsewhere in the network.

These findings about asymmetry hold in experiments with artificial power grids. At the American Physical Society meeting in Boston last month, Motter presented unpublished results suggesting that “generators can more easily oscillate at the exact same frequency, as desired, if their parameters are suitably different,” as he put it. He thinks nature’s penchant for asymmetry will make it easier to stably sync up diverse energy supplies. “A variety of tasks can be achieved by a suitable combination of synchrony and asynchrony,” Kuramoto observed in an email. “Without a doubt, the processes of biological evolution must have developed this highly useful mechanism. I expect man-made systems will also become much more functionally flexible by introducing similar mechanisms.”

Adapted from Quanta Magazine

How My Nobel Dream Bit the Dust

My team thought we’d proved cosmological inflation. We were wrong.

“You may speculate from the day that days were created,
but you may not speculate on what was before that.”
—Talmud, Tractate Hagigah 11b, 450 A.D.

To go back to the beginning, if there was a beginning, means testing the dominant theory of cosmogenesis, the model known as inflation. Inflation, first proposed in the early 1980s, was a bandage applied to treat the seemingly grave wounds cosmologists had found in the Big Bang model as originally conceived. To call inflation bold is an understatement; it implied that our universe began by expanding at the incomprehensible speed of light ... or even faster! Luckily, the bandage of inflation was only needed for an astonishingly minuscule fraction of a second. In that most microscopic ash of time, the very die of the cosmos was cast. All that was and ever would be, on a cosmic scale at least—vast assemblies of galaxies, and the geometry of the space between them—was forged.

For more than 30 years, inflation remained frustratingly unproven. Some said it couldn’t be proven. But everyone agreed on one thing: If cosmologists could detect a unique pattern in the cosmos’s earliest light, light known as the cosmic microwave background (CMB), a ticket to Stockholm was inevitable. Suddenly, in March 2014, humanity’s vision of the cosmos was shaken. The team of which I had been a founding member had answered the eternal question in the affirmative: Time did have a single beginning. We had proof. It was an amazing time indeed.

For weeks I had known it was coming. Our entire team was furiously working to finalize the results we would soon make public. We had relentlessly reviewed the data, diligently debating the strength of the findings, discussing what could be one of the greatest scientific discoveries in history. In the intensely competitive world of modern cosmology, the stakes couldn’t have been higher. If we were right, our detection would lift the veil on the birth of the universe. Careers would skyrocket, and we would be forever immortalized in the scientific canon. Detecting inflation equaled Nobel gold, plain and simple.

But what if we were wrong? It would be a disaster, not only for us as individual scientists but for science itself. Funding for our work would evaporate, tenure tracks would be derailed, professional reputations ruined. Once gleaming Nobel gold would be tarnished. Glory would be replaced by disappointment, embarrassment, perhaps even humiliation.

The juggernaut rolled on. The team's leaders, confident in the quality of our results, held a press conference at Harvard University on March 17, 2014, and announced that our experiment, BICEP2, had detected the first direct evidence of inflation—evidence, albeit indirect, of the very birth pangs of the universe. BICEP2 was a small telescope, the second in a series of telescopes located in Antarctica. I had co-invented the first telescope (BICEP) more than a decade earlier, when I was just a lowly postdoc at Caltech. BICEP sprang out of a deep obsession I had long had with making the invisible birth of the universe visible. And it wasn't lost on me that, if we succeeded, the Nobel Prize would be the most tangible reward for the discovery.

BICEP's design was simple. It was a small refracting telescope—a spyglass like Galileo's, with two lenses that bent incoming light and directed it not to the human eye but to modern, ultrasensitive detectors. The telescope needed to be at an exquisitely pristine location, and we found one: the South Pole. Our goal was to capture the aftershocks of cosmic inflation, a signal imprinted on the afterglow of the Big Bang—the CMB, which permeates all of space.

For years BICEP2 looked for a swirling, twisting pattern (called a B-mode polarization pattern) in the CMB that cosmologists believed could only have been caused by gravitational waves squeezing and stretching space-time as they rippled through the infant universe. What could have caused these waves? Inflation and inflation alone. BICEP2's detection of this pattern would be evidence of primordial gravitational waves generated during inflation, all but proving that inflation happened.

Then we saw it. There was no going back. The broadcast from Harvard's Center for Astrophysics captivated media around the world. Nearly 10 million people watched the press conference online that day. Every major news outlet, from The New York Times to the Economist to obscure gazettes deep within the Indian subcontinent, covered the announcement "above the fold." My kids' teachers had heard about it. My mother's mahjong partners were kvelling about it.

Watching the live video, I could see MIT cosmologist Max Tegmark reporting the event. He wrote, "I'm writing this from the Harvard press conference announcing what I consider to be one of the most important scientific discoveries of all time. Within the hour, it will be all over the web, and before long, it will lead to at least one Nobel Prize." Finally, we'd seen what we, and the whole world apparently, had wanted to see. The BICEP2 team's announcement was that we had read the very prologue of the universe—which, after all, is the only story that doesn't begin in medias res. Still, doubts plagued me. It sure seemed to be a discovery for the ages. But was it? No one is immune from confirmation bias. And scientists, despite what you may think, are rarely mere gatherers of facts, dispassionately following data wherever it may lead. Scientists are human, often all too human. When desire and data are in collision, evidence sometimes loses out to emotion. It was impossible to rule out every possible contaminant. Had we fretted enough?

The most worrisome aspect of BICEP2's signal was how huge it was. It was shockingly big, more like finding a crowbar in a haystack than a needle, as one team member phrased it. At the time of our announcement, we were worried about being beaten by our chief competitor, a $1 billion space telescope called the Planck satellite with the perfect heavenly perch from which to scoop us. Prior to BICEP2's press conference, Planck had already ruled out a B-mode signal half as big as the one we claimed to have observed. Cosmologists were expecting a whisper. We claimed BICEP2 had heard a roar.

Planck represented serious competition: It had a heavenly vantage point 1 million miles above Earth, free from gravity and atmospheric contamination alike. Planck possessed the perfect perch from which to scoop us. Worse yet, the BICEP2 telescope had been disassembled two years earlier. We couldn't exactly go back and check to see if we had taken the lens cap off. But we could make use of our most powerful weapon: data, and lots of it. We began by testing it for consistency by dividing the massive data set in half and making two maps, one from BICEP2's first 18 months of observations and one from the second 18 months. The two maps showed the same signal, albeit with lower signal-to-noise ratio (because each map had only half the amount of data as the two maps put together).

To prevent mistakes, carpenters say, "Measure twice, cut once." Well, BICEP2 astronomers cut the data dozens of ways, looking for discrepancies in data from one set of detectors versus another, or differences between when the telescope was scanning to the right versus to the left. We tortured the data in every conceivable way, each scientist on the team trying to concoct ever more outlandish scenarios that we had overlooked. Even if extraterrestrials had created our signal, the implications might have been less astonishing! When I speak in public and am introduced as a cosmologist, I like to joke that you sure don't want me doing your hair and nails. Many people don't know that the similarity between cosmology and cosmetology is more than skin deep. They both have the prefix cosm, which is the Greek word for "adornment," as in the beautiful face the universe shows us. When I saw the BICEP2 data arranged into a map, the pattern of whorls and swirls took my breath away. It was exactly what inflation predicted we'd see, and it was love at first sight. The cosmos wasn't just beautiful. It was showing off.

Our exhilaration was mixed with a sense of foreboding. After a yearlong inquisition, it became clear: The signal was not coming from the South Pole, the atmosphere, nor BICEP2 itself. Where else could it be coming from, if not inflation? One possible answer was that we'd seen the same material that had bedeviled so many astronomical discoveries since Galileo's time: dust. Everyone knew that B-modes could come from interstellar dust in the Milky Way: Microwaves scattering off dust within our own galaxy could generate the pattern we saw. Might it make up the entire signal we were now seeing? How could we prove it was not dust, but the imprint of gravitational waves on the cosmic microwave background?

Though we had selected the Southern Hole—the patch of sky where BICEP2 hunted for B-modes—based on the low level of dust predicted by the best available models, we didn't know for sure if it was as free of contamination as we'd expected. What we really needed were high-frequency data.

Earlier I mentioned that the amount of polarization produced by dust increases very steeply with frequency. BICEP2 worked at 150 GHz only, corresponding to wavelengths of approximately 2 millimeters. Doubling the frequency would more than triple the dust signal. If dust were producing our B-modes, it would be obvious at 300 GHz ... if only we had data at such high frequencies.

In truth, such a map did exist, one with the exact high-frequency data we needed. There was only one catch: It belonged to our competitor, the Planck satellite. And in early 2014, the Planck team hadn't yet released their B-mode polarization data. We were scared Planck might not only hold the key to proving our measurement right, but might have already glimpsed the inflationary B-mode signal before we did. If it really was as large as we thought it was, it was well within Planck's grasp.

We desperately tried to work with the Planck team, while being careful not to tip them off as to what we'd found. It was a perilous line to walk. Science teams that sometimes collaborate can be in competition at other times, particularly when there is a well-known goal or target signal both are looking for. This is a troublesome aspect of science; many of us treat the data as if it's "ours" when, in fact, it belongs to the people paying the bills: the taxpayers.

BICEP2 had much more sensitive data, but Planck's was broader, covering the whole sky and at many more frequencies than BICEP2 had. After everything else was ruled out, frequency coverage held the key to our fate. The Planck team wouldn't cooperate. Either they didn't have the data we wanted, or they did have it and they were going to scoop us. We had to go it alone. What BICEP2 lacked in frequency quality, we compensated for with quantity. We made five different models for the dust, each based on old data—the same data that we'd used to choose BICEP's observing region nearly a decade before.

Each of the five models predicted the total emission—the total heat produced by dust—at a particular region in the galaxy, but none of them could predict how much polarization we could expect in the Southern Hole. So, from these data, we extrapolated what galactic dust emission would look like in our patch if it were also slightly polarized. We played the guessing game, trying to be conservative, and eventually settled on a level of about 5 percent for our simulations.

Then came a revelation: We noticed that a Planck team member, Jean-Philippe Bernard, an expert on the Milky Way's polarization, had given a talk earlier that year which was posted online. Bernard showed an actual picture of Planck's dust measurements: a map of the sky as seen by our competition. It was a treasure map, with polarized "X"s marking the spot of sure Nobel gold.

As soon as we discovered it, one of our team members digitized Bernard's slide, revealing by extrapolation the formerly forbidden Planck data. We knew it was an unorthodox approach. In fact, it didn't sit well with many of us. We took unpublished data, a single qualitative image, and digitized it, turning it into quantitative information. By doing so, we obtained a new model, one unavailable when we began taking data with BICEP, with exactly the information we craved.

Planck had not published this map and they likely had their own systematic errors to worry about. But the slide was public and freely available, giving us the green light to use it if we explained our methodology. But, if we went public, how much weight should this contraband slide carry? At first it was a curiosity, a digital trick to make us feel more confident. Then, a few months later, it snowballed, becoming a major link in the chain of reasoning assuring us that galactic dust was safely ignorable … and confirming something beyond our wildest hopes when we started: We had discovered B-modes from inflation.

Using the slide made me uncomfortable. On conference calls and in emails I complained to BICEP2's leaders. I wanted clarification: Were we sure we had accurate measurements of dust? I was concerned that BICEP2's results had already been ruled out by Planck. Polarization of dust was the most obvious explanation for a signal we could see that Planck couldn't. "How can we use slides that were shown in a talk but not intended for any quantitative purpose?" I asked in an email to the whole team. The leadership replied to my email, saying that it was fine to use the slide if we stated the assumptions we'd made.

Plus, the Planck slide merely confirmed the results of the other five models we had, all of which showed that dust wasn't a plausible explanation for the bright B-modes we saw. Planck's slide would be but one piece of evidence, and not the most definitive piece of evidence at that. That distinction belonged to my precious BICEP, which had been renamed BICEP1. Unlike BICEP2, which observed the sky at a single frequency—150 GHz, where the CMB is brightest—BICEP1 had three frequency channels, at 90, 150, and 220 GHz. With the benefit of these other frequency channels we could exclude, to some extent, the impact of dust above a certain level.

We could use Planck's slide, because it wasn't the main line of evidence. That most convincing evidence came courtesy of BICEP1, which said dust wasn't the cause of our signal, and we were 95 percent confident about that. In other words, dust had only 1 chance in 20. Would you enter a lottery, the biggest one in cosmic history, if you had "only" a 95 percent chance of winning? Of course you would!

John Kovac made one last plea to the Planck team for their actual data, but again was denied. I figured Planck was about to scoop us. Waiting wasn't going to help. The Planck slide combined with BICEP1's data convinced all 49 of us, including me. I got off of my high horse. It was time: Publish, or else our Nobel dreams might perish.

Within three weeks of the press conference, 250 scientific papers had been written about our results. That was astonishing; a paper is considered "famous" if it has 250 citations over the course of decades! Then, in early April, I got an email from the physicist Matias Zaldarriaga. How many times can he be congratulating me, I wondered? "When the dust is low, but spread over a wide area, it betokens the approach of infantry." —Sun Tzu, The Art of War

Matias's April email was no "attaboy." He was disturbed. He wanted to talk details. What did I know and when did I know it? It was the beginning of a trial I had long feared. Rumors were swirling at Princeton about the way we had used the infamous Planck slide. “People here in Princeton are very concerned about dust,” he said, ominously adding, “In fact they have managed to convince me that there is not a very good reason for me to believe it is not just dust. Have you looked into the foregrounds yourself?” Of course I had looked at the foregrounds—potential sources of contamination such as polarized emission from the Milky Way’s dust. The whole team had been worried about our galaxy producing spurious B-mode polarization that would masquerade as primordial gravitational wave B-modes. But data at low frequencies from BICEP1 and at high frequencies from Planck’s scrubbed PowerPoint slide convinced us we were okay.

A few days later, I got wind of a colloquium that Princeton University’s David Spergel had given just after the Harvard press conference. David said he had spotted a blunder in our results, that our data were contaminated by dust within the Milky Way galaxy. Soon, I found out there were others at Princeton laser-focused on the way we modeled dust. The BICEP2 leadership had anticipated an onslaught, perhaps even a backlash, from the Princeton folks, who were working on several competing B-mode experiments. Maybe they were just frustrated after being scooped on another major CMB discovery.

I asked Matias if it was David Spergel alone causing his concerns. Ominously, Matias said, “I think there is nothing else people here talk about.” My heart stopped. Princeton’s cosmology program is the top-ranked in the country—cosmology’s own Holy See, comprised of the world’s best experimentalists and theorists, among them multiple members of the National Academies of Sciences. It felt like an inflationary Inquisition, one that could put the BICEP2 results on a modern-day Index of banned pre-prints. Imagine finding out the entire IRS is obsessed with your tax return. Not just one rogue auditor, but everyone, from the Secretary of the Treasury on down, fixated on your Form 1040! It was petrifying.

Matias told me that an outstanding young physicist named Raphael Flauger was leading a paper with Spergel and Spergel’s graduate student J. Colin Hill. Flauger had convinced Matias that the Milky Way’s dust polarization was higher than what the BICEP2 scientists had assumed. We were vulnerable to the same sort of tactics we had employed in utilizing the unpublished Planck slide; they could digitize our results before we released them. Live by the slide, die by the slide. Matias added, “Don’t get me wrong. Obviously, there is nothing more I would want than the result to be correct. But the discussions here have shaken my confidence and thus I hope you guys respond to the skeptics with a detailed explanation of exactly what you did with those Planck slides.”

By early May, Flauger and his collaborators had finished their analysis, and it didn’t look good for BICEP2. According to Flauger, we had used an incorrect estimate of the level of dust polarization in the Planck slide, a value four times lower than we should have used. If true, BICEP2 would go down as the most celebrated dust detector in history—tricked, like so many before us, by a dirty mirage. But Flauger’s analysis wasn’t conclusive. He himself remained dispassionate, saying, “I hope there still is a signal. I’m not trying to pick a fight; this is how science works, that someone presents a result and someone else checks that. But it doesn't usually happen in public like this." He and his colleagues, as well as Uroš Seljak and Michael Mortonson, claimed our interpretation of Planck's results was suspicious; but this didn't mean we were wrong. Only new data, data unavailable to either BICEP2 or the groups doing the reanalysis, could tell us if the ax would eventually fall. The jury was still out.

Flauger's analysis was thorough, and it took several weeks for the cosmology community to digest it. A tense atmosphere settled over the CMB community; this was a cosmic cliffhanger, slowplaying us all. The beginning of the summer found the BICEP2 team in full panic mode, analyzing and reanalyzing data, responding to referee reports and putting out fires in the media and at scientific conferences. Paralleling our scientific battles was a battle in the media about the media. In particular, the propriety of the Harvard press conference became one of the hottest topics in all of science. The criticism we received about the way BICEP2 sought publicity was almost as intense as the heat we took for using the scrubbed Planck PowerPoint slide.

Scientists, pundits, and journalists alike questioned the decision to announce our findings at a press conference before peer review had been completed. While it's impossible to know whether holding a press conference was good or bad for us specifically, the issue of if, and when, press conferences should be held is an important question. Such decisions are always stressful. For a physicist, a press conference is likely a once-in-a-lifetime event. If your results are correct, a press conference-worthy discovery might result in a Nobel Prize. If your result is erroneous, it might be the end of your research ... and its press coverage.

For BICEP2, the standard practice—a months-long peer review process, which would then be followed by a press release—had many disadvantages, any of which, individually, were worrisome. In total, they were completely unpalatable. First off, during the peer review, rework, and resubmission cycle we could have been scooped by the competition. Second, we feared that sending the paper to a journal would be unfair, giving a particular group—referees and their friends—a head start on proposal submission. My field is so competitive that the only people who weren't on BICEP2 who could have reviewed the highly technical aspects of the paper were competitors. Our first priority was to make a scientific presentation to communicate our results to all our peers in the cosmology community. By releasing BICEP2's papers and data online, we allowed the entire community, not just two referees, to immediately begin a technical review. While some scientists praised our decision to go public first, analogizing our decision to the announcement of a blockbuster new drug, the criticism of BICEP2's crowdsource approach was, at times, brutal. New York Times reporter Dennis Overbye noted that this approach to the scientific sausage-making process wasn't pretty, calling it a "dissection ... a rare example of the scientific process—sharp elbows, egos and all."

Three months after the press conference, in June 2014, the peer-reviewed version of the paper was published in Physical Review Letters. Taking the advice of two anonymous referees, we removed all trace of the dust data we took from Planck's PowerPoint slide. Its deletion, we said, was due to the unquantifiable uncertainties involved in its analysis. But we were clear: BICEP2's data were unimpeachable. It was only the interpretation which was up for debate. Planck promised to resolve the situation soon, because its newest data was set to be released in the next few months.

Planck had previously shown that the Milky Way's dust emitted microwaves with a blackbody spectrum, just like the CMB. But the dust emission had a temperature of 20 Kelvin, instead of 3 Kelvin. Since the total energy of a blackbody increases as the fourth power of its temperature, the Milky Way's emission was nearly 2,000 times brighter than the CMB's emission.

One of Planck's channels, its frequency band at 353 GHz, was nearly insensitive to anything besidesdust; it was a kind of sacrificial channel dedicated not to the cosmological gold we sought, but to the cosmic schmutz that might be obscuring it. We all held out hope that Planck's 353 GHz channel would be the salvation, quantifying the qualitative PowerPoint slide and allowing an unaltered conclusion. It was going to be a long, hot summer.

With the Planck 353 GHz paper appearance came the beginning of the end of the BICEP2 team's inflation elation. Although the Planck team was careful to release no data for the Southern Hole, the field where BICEP2 observed—perhaps out of fear we would digitize it—they made a blunt assessment of the potential amount of dust polarization contamination in the Southern Hole, saying it was of "the same magnitude as reported by BICEP2." This meant dust was as likely a culprit for our B-modes as were inflationary gravitational waves.

Later, the Planck team produced an image of the Milky Way's dust polarization, finally including our patch of sky, the Southern Hole. It was mesmerizing; large swaths of sky festooned with azure streamers, whorls of ocher, and swaths of amber garland. Dust was showing off in all its Van Gogh vainglory. "Visible certainty," Galileo likely would opine, as he had with his Pleiades hypothesis. But this time he'd be devastatingly right. It was over. Eden had sunk to grief. Our Nobel gold couldn't stay.

BICEP2 turned out to be a very precise dust detector. It also showed the public how science works: You put out a result, and other scientists work to test the result. You put your cards on the table, and leave it all out there for your critics. If and when they attack, you defend until you can defend no longer and the attacks subside. Only then, when both critic and supporter collapse, exhausted, can science be said to be settled. For the BICEP2 retraction, there was neither press conference nor viral YouTube video. And while Planck, the fearful enemy fighter on our tail, came clean about the amount of dusty B-modes that our galaxy produced, they never did say anything about cosmic B-modes produced by inflation. It was BICEP2's vision which was clouded: a bit by fear, a bit by greed, and mostly by bits of dust.

Adapted from Nautilus

Time to update the Nobels

Science today is an intricate, collaborative, global enterprise. Nobel prizes for individual scientists are an anachronism

Imagine the outcry if, at the 2016 Summer Olympics, the legendary United States swim team – Michael Phelps, Ryan Lochte, Conor Dwyer and Townley Haas – still obliterated the competition, coming first in the men's 4 x 200m freestyle relay, but only Haas, Lochte and Dwyer received medals, with nothing, not even a silver, for Phelps. 'Unfair!' you'd cry. And you'd be right. The Nobel committee seems not to recognise how collaborative science is today; their paradigm remains the lone genius, or a duet or troika at most. Year after year, they perform their arbitrary and often cruel calculus, leaving deserving physicists shivering in the pool without any medal to show for it. Even those few modern experimentalists who have won unshared Nobel prizes owe their success to numerous collaborators – especially in particle physics and astronomy, which require massive data sets and large teams to analyse them. No scientist gets to Stockholm alone.

The 2013 Nobel Prize in Physics, which was given to Peter Higgs and François Englert for the theoretical prediction of what was later called the Higgs boson, exemplifies four key problems in the selective awarding of the prize. First, it went to only two scientists (even though the committee allows three winners), when there were six other physicists, working in several teams, who independently introduced the idea and could rightfully claim joint custody of the Higgs mechanism. Higgs himself calls the it 'the ABEGHHK'tH mechanism', standing for Philip Anderson, Robert Brout, Englert, Gerald Guralnik, Carl Richard Hagen, Higgs, Tom Kibble and Gerard 't Hooft. All except Brout were still living in 2013. Second, none of the more than 6,200 experimentalists who helped make the detection at the Large Hadron Collider (LHC) will ever win a Nobel Prize. If the committee would even allow itself the indulgence of four laureates per prize, at least the two leaders of the ATLAS and CMS experiments at the LHC might have had a share. In stark contrast, the 2017 Nobel Prize was awarded only to the instrumentalists who'd built the Laser Interferometer Gravitational-Wave Observatory (LIGO) experiment, which was designed to detect cosmic gravitational waves – ripples in space-time caused whenever massive objects move. Of course, the theorist who had predicted the existence of the gravitational waves that LIGO detected, Albert Einstein, had died 62 years earlier. Even I, who believe the Nobel should be awarded posthumously, think that's stretching it. Third, the award of the prize to Higgs and Englert blocked everyone else associated with the Higgs boson, whether experimentalists or theorists, from winning one. Even in clear-cut cases where historians agree that the Nobel committee made a mistake, never has more than one Nobel Prize been awarded per discovery or invention. Doing so would be tacit condemnation of earlier prize committees. Fourth, the committee made clear that it prefers to confer no more than one Nobel Prize per person. (Only one laureate, John Bardeen, has won two Nobel prizes in physics.) So, since 't Hooft had already won a Nobel Prize in 1999 (for 'elucidating the quantum structure of electroweak interactions'), the committee gave the 2013 prize to two first-time winners, despite the enormous role ’t Hooft had played. If the Nobel Prize is a true meritocracy, a scientist should be eligible to win it as many times as she or he makes a prize-worthy discovery. By that standard, Einstein might have had as many as seven Nobel prizes. That would certainly comport with his reputation among his fellow physicists.

In truth, winning ‘only one’ Nobel Prize isn’t such an awful fate, even if it is shared. If the Nobel Prize were given to groups, the prestige of being a laureate would hardly be diminished; the fraction of the Nobel Prize a laureate receives is irrelevant, except in terms of the prize money (one-quarter of the total sum is the minimum amount a laureate can win). All winners receive the same 18-carat gold medal. Technically, Arno Penzias and Robert Wilson, co-discoverers of remnants of the early Universe called cosmic microwave background radiation, each won a quarter of the prize; the other half was awarded for completely unrelated work, as a sort of lifetime achievement award to the Russian physicist Pyotr Leonidovich Kapitsa ‘for his basic inventions and discoveries in the area of low-temperature physics’. Indeed, to the extent that fame is important, and I do believe it is, an educated layperson might know about Penzias and Wilson, but no layperson has heard of Kapitsa, even though he ended 1978 with twice as much cold hard Nobel cash as Penzias and Wilson did. And no one ever says: ‘Oh, Penzias, he only won a quarter of a Nobel Prize!’

Alfred Nobel himself was an inventor, and he was used to filing patents to ensure that his claims were properly staked. When he wrote his will, in the late 19th century, science was done, if not strictly by loners, by single scientists with, at most, a handful of lab technicians. (They didn’t have the students we professors rely on as our ‘force multipliers’ today.) Had the Nobel Prize existed back then, Galileo would have won it in 1611, the year after he announced his serendipitous telescopic observations – and would not have shared it. No other invention, before or since – not the atom smasher, the X-ray, not even the automatic regulators used in conjunction with gas accumulators for illuminating lighthouses and buoys – had the transformative impact on physics, philosophy and even theology that Galileo’s telescope did; within weeks, it was clear that his telescopic observations had moved mankind away from the centre of the Universe. Copernicus, whose principle Galileo had verified, was long dead by 1611, rendering him ineligible. Hans Lippershey, widely credited with inventing the telescope, never actually observed the heavens with it, nor did his version have sufficient magnification to reveal the phases of Venus and the moons of Jupiter, which ultimately provided decisive evidence for the Copernican hypothesis.

It did not take long for the Royal Swedish Academy of Sciences to jettison the strict interpretation of Nobel’s will. In the prize’s second year, 1902, Hendrik Antoon Lorentz and Pieter Zeeman jointly won a sort of lifetime achievement award ‘in recognition of the extraordinary service they rendered by their researches into the influence of magnetism upon radiation phenomena’. The prize was not given for a single discovery or invention (and, of course, their ‘service’ hadn’t happened in the previous year either). Following that, Henri Becquerel and Pierre and Marie Curie won for their work on radioactivity. In the two decades that followed, there were 19 sole laureates. In contrast, the list of recent single laureates is small indeed. The last sole winner in physics was Georges Charpak in 1992.

It's still rare for more than a handful of theorists to discover a theory at the same time. By nature, theoretical discoveries are serendipitous, and serendipity doesn't lend itself to multiples; three simultaneous lightning strikes are rare. Nowadays, it's much harder to be a sole laureate if you are an astronomical observer or an experimental physicist. It wasn't always this way. Science was less collaborative in years past. More than 20 of the first 30 Nobel prizes in physics went to inventors or experimentalists, not theorists. The reason for this is shameful but, thankfully, since abolished: in the early 1900s, European intellectuals derided theoretical investigations as anathema to physics, unworthy of Nobel consideration. The physicists who nominated laureates, some of whom were laureates themselves, considered pure theoretical investigations such as Einstein's special relativity 'Jewish physics'. Real physicists did experimental physics.The movement away from lone laureates to multiple winners has accompanied near-inflation-like growth in all scientometrics – the metrics by which science, technology and innovation are measured. The science historian Derek de Solla Price locates the inflection point in the 'hockey stick' growth curve at the Second World War, when teams of physicists were kept 'locked away in interacting seclusion. We gave them a foretaste of urgent collaboration in nuclear physics, and again in radar.' By any metric, the image of the solitary researcher increasingly seems to become marginalised as a relic from the past.

This was the beginning of the period that Price in 1963 called 'Big Science', when research projects in all fields of science enjoyed exponential growth, creating a feedback loop that has taken us from entire fields with only 100 researchers to single papers with 10 times as many authors. We've gone from the Royal Society to the Large Hadron Collider in just over a century. Today, the situation seems irreversible. While there is still diversity in the size of groups, many big projects with big goals require big telescopes and big-dollar amounts. The biologist and philosopher Hub Zwart describes the ratchet-like behaviour of Big Science as not only referring 'to the actual number of researchers working and collaborating within a particular field, but also to the increased dependence of current research on massive, expensive and sophisticated technologies' such as LIGO or the LHC. With so many stakeholders, it shouldn't be surprising that the competition to win the Nobel Prize is extremely fierce. Of course, not all competition harms science; competition can also be healthy. It lends credibility to new discoveries: a signal detected by a single group doesn't mean that much without corroboration, and truly settled science becomes possible when more than one team gets the same results. Multiple groups are needed to rule out mistakes and validate findings. Yet excessive competition leads to wasted resources, the impetus (sometimes resisted, sometimes not) to publish prematurely, and a ruthless winner-takes-all battle to get there first so as to capture the dwindling dollars from federal funding sources in decline. The size of new scientific projects, especially experimental ones such as large telescopes or particle accelerators, makes the competition only worse. Funding agencies are partially at fault for the climate of scientific competition, as the Nobel laureate Saul Perlmutter, an outspoken critic of the current funding environment, has explained. Perlmutter's team, the Supernova Cosmology Project, was in a fierce battle with a rival team, the High-Z Supernova Team, to measure how the Universe's expansion was slowing down over time. 'They would race us to the results,' Perlmutter has said. 'Probably 90 per cent of all the people on Earth working on supernovae were involved in one of the two projects. It was a fiercely fought race. We wouldn't tell each other anything that was going on.

We would be flying to the same telescopes they had just finished with.' To their astonishment, the two teams independently found that the Universe wasn't slowing down at all. Its expansion rate was, instead, speeding up. They had found evidence for dark energy, a mysterious form of antigravity– a latter-day version of inflation. Though they were in direct competition, members of both teams won the Nobel Prize. In a study of the publication dynamics of Nobelists, the science historian Harriet Zuckerman has found that laureates collaborate with more co-workers than a matched sample of non-laureate scientists. Yet, she observes, since the current rules compel the committee to overlook an increasing number of collaborating scientists, the award of the Nobel Prize to no more than three members often leads to the collaboration dissolving soon afterward. Surely, this is not in the best interests of science.

I'd prefer that scientists be guided by the man who was the father of my field of observational cosmology. Robert Dicke declined Penzias's offer to be a third author on the Nobel Prize-winning CMB discovery paper, a decision that likely cost him a share of the 1978 Nobel Prize. While he might have lost out on science's top award, Dicke's group (at Princeton University) joined Penzias and Wilson's (at the private Bell Labs) to form a public-private partnership that allowed the Big Bang theory to achieve a wide acceptance. Recently, the most powerful scientific organisation of its kind drastically changed the way it hands out its golden prizes. In 2009, the Academy of Motion Picture Arts and Sciences (yes, sciences) doubled the number of Best Picture Oscar nominees from five to 10, opening the wellsprings of credit to flow more fully. Both the Nobel prizes and the Academy awards are meritocratic, determined by peers and ostensibly egalitarian, with no heed paid to commercial success. Both ceremonies are televised live, from giant halls filled with pomp and circumstance, and guests in resplendent regalia. Winners receive golden idols from royalty, of the Swedish and Hollywood varieties. While Hollywood doesn't adhere to Nobel's stipulation that actors provide the 'greatest benefit to mankind', there is a humanitarian award and a definite, if self-congratulatory, sense that the industry can influence society for the better. When the physics Nobel Prize winners were announced in 2012, the physicist Jim Al-Khalili made several suggestions for modernising the prize in an opinion piece in The Guardian. He piqued my attention when he wrote: Most Nobel prizewinners will have carried out their breakthrough work for many years before they are recognised with the prize, and probably long after they had given up hope of that ultimate accolade – these are not the Oscars, after all, where an actor at least knows that he or she has made it to a shortlist …For the rest of the scientific community around the world, this is also a time to hope that the winner comes from one's own particular area of research, boosting the chances of bathing in reflected glory and gaining valuable research funding.

Al-Khalili's comment made me wonder: what if the Nobel committee recognised all the nominees each year? Currently, the names of the nominees (and nominators) are kept secret for 50 years. Why must the names of those who came close to winning the Nobel Prize be classified as if they were part of the Warren Commission report on the assassination of JFK? The reason given by the Royal Swedish Academy of Sciences for the secrecy around nominations is to avoid upsetting nominees who do not win. This seems like a weak argument. Even though it's a cliché, Oscar also-rans often say: 'It was an honour just to be nominated!' Announcing the nominees would benefit the fields that are nominated as well. Scientists in those fields would receive more prominence and potentially more funding, just as those in the winner's field do, as Al-Khalili pointed out. It would also be gratifying, as a nominator, to know that your choice was considered. It's an honour to be a nominator, which I've been, but if your nominee doesn't win, perhaps you won't waste your next opportunity on nominating the same person (assuming, of course, you haven't written a book critical of the Nobel Prize process, and thus scuttled your chances of a follow-up invitation).

Of course, you might contend that revealing all the nominees could take away from the winner's lustre, and put the attention on others instead of the winner. But, in practice, neither is likely to happen, just as it does not happen in the Academy Awards. Nobel Prize winners will always, rightfully, be recognised as society's fifth-degree black-belt intellects. And, they will continue to rack up awards, seeing as they've already received the ultimate accolade. In fact, they might appreciate some time out of the spotlight: the time demands on laureates are infamous, leading T S Eliot to opine: 'The Nobel is a ticket to one's funeral. No one has ever done anything after he got it.' As aloof as scientists are toward celebrity, we could learn from our artistic counterparts. Hollywood's version of inflation is not of the cosmological sort, but regards recognition. According to an article in The New York Times, 'Who Was That Food Stylist? Film Credits Roll On' (2004), the time it takes to roll the credits for a major Hollywood movie is pushing 10 minutes – triple the time it took the Universe to make almost all of its hydrogen nuclei.

Modern Hollywood, like modern science, is more collaborative than ever. Figure 1 below shows the number of credited cast and crew members (from director and starring actors to bird wrangler and on-set florist, as well as the vast teams creating computer-generated imagery) in Best Picture Oscar-winning films since the awards' inception in 1927. Compare this with figure 2 below, which shows the number of credited collaborators on prize-winning discovery papers since the Nobel's inception in 1901. Both graphs show a characteristic ‘hockey stick’ shape, increasing dramatically since the first Nobel Prize to Wilhelm Röntgen (one person) and the first Oscar for Best Picture to Wings (23 credited cast and crew), to 6,225 combined co-authors on the ATLAS and CMS experiments at the LHC, and 353 credited contributors to 2014’s Best Picture winner, 12 Years a Slave.

Hollywood has Stockholm beat when it comes to credit and awards; everyone involved with each year’s Best Picture award receives a share of the credit. So too does each producer – Hollywood’s version of the principal investigator – receive an Oscar for bringing the winning film to fruition. Artificially imposing a maximum of three Nobel laureates merely fosters unnecessary competition, and there’s enough of that in science already. Why not an eight-fold cord, for the ABEGHHK’tH mechanism? Or a 1,000-stranded cord for all of those who collaborated on LIGO? As the historian Elisabeth Crawford has pointed out, the original statutes of the Nobel Foundation didn’t forbid awarding the physics prize to a group: ‘In cases where two or more persons shall have executed a work in conjunction, and that work be awarded a prize, such prize shall be presented to them jointly.’

Some have complained that giving a share in the physics prize to every scientist involved would devalue the award, decreasing the well-earned attention that the originators of the project deserve. Yet awarding the Nobel Peace Prize to groups has in no way decreased its prominence. The peace prize can be awarded to groups, individuals, or groups and individuals (as was the case, for example, with the 2007 prize, half of which was awarded to the Intergovernmental Panel on Climate Change, and the other half to the former US vice president Al Gore). Especially in experimental science, where collaboration is essential, expanding recognition would help convince young people to take more risks in the ideas and projects they pursue. For me personally, the most rewarding aspect of my job is working with scientists from all over the world, from Uganda to Ukraine, from Thailand to Texas, on every continent including Antarctica. It’s high time the Nobel Prize reflects the true reality of modern physics: the best science of all is the most collaborative.

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