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ILLUMINATING PHYSICS:

part 1

Учебное пособие

Саратов

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Table of Contents

PREFACE

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

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

Пособие состоит из 5 разделов, рассматривающих проблемы и достижения в сфере информационных технологий в современном мире. Каждый из них содержит аутентичные материалы (источники: *Aeon, Nautilus, Vox*) 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. The biggest problems facing science, according to 270 scientists

Exercise I.

Say what Russian words help to guess the meaning of the following words: problems, political, career, serious, institution, epidemic, result, process, ideal, elegant

Exercise II.

Make sure you know the following words and word combinations.

Fierce, paywall, perverse, caveat, to nudge, yield, bias, staggering, outlier, grinding

The biggest problems facing science, according to 270 scientists

Science, I had come to learn, is as political, competitive, and fierce a career as you can find, full of the temptation to find easy paths

In the past several years, many scientists have become afflicted with a serious case of doubt — doubt in the very institution of science. We wanted to understand this epidemic of doubt. So we sent scientists a survey asking this simple question: If you could change one thing about how science works today, what would it be and why? We heard back from 270 scientists all over the world and they told us that, in a variety of ways, their careers are being hijacked by perverse incentives. The result is bad science.The scientific process, in its ideal form, is elegant: Ask a question, set up an objective test, and get an answer. But nowadays, our respondents told us, the process is riddled with conflict. Scientists say they’re forced to prioritize self-preservation over pursuing the best questions and uncovering meaningful truths. Today, scientists' success often isn't measured by the quality of their questions or the rigor of their methods. It's instead measured by how much grant money they win, the number of studies they publish, and how they spin their findings to appeal to the public. Scientists often learn more from studies that fail. But failed studies can mean career death. So instead, they’re incentivized to generate positive results they can publish. And the phrase "publish or perish" hangs over nearly every decision. The selection pressures in science have favored less-than-ideal research: "As long as things like publication quantity, and publishing flashy results in fancy journals are incentivized, and people who can do that are rewarded … they’ll be successful, and pass on their successful methods to others." Many scientists have had enough. They want to break this cycle of perverse incentives and rewards. In our survey and interviews, they offered a wide variety of ideas for improving the scientific process and bringing it closer to its ideal form. Some caveats to keep in mind: Our survey was not a scientific poll. For one, the respondents disproportionately hailed from the biomedical and social sciences and English-speaking communities. Many of the responses did, however, vividly illustrate the challenges that scientists across fields face. And they are a valuable starting point for a deeper look at dysfunction in science today. The place to begin is right where the perverse incentives first start to creep in: the money.

Academia has a huge money problem. To do most any kind of research, scientists need money: to run studies, to subsidize lab equipment, to pay their assistants and even their own salaries. Our respondents told us that getting — and sustaining — that funding is a perennial obstacle. Their gripe isn’t just with the quantity, which, in many fields, is shrinking. It’s the way money is handed out that puts pressure on labs to publish a lot of papers, breeds conflicts of interest, and encourages scientists to overhype their work. In the United States, academic researchers in the sciences generally cannot rely on university funding alone to pay for their salaries, assistants, and lab costs. Instead, they have to seek outside grants. In many cases the expectations were and often still are that faculty should cover at least 75 percent of the salary on grants.Grants also usually expire after three or so years, which pushes scientists away from long-term projects. Yet as John Pooley, a neurobiology postdoc at the University of Bristol, points out, the biggest discoveries usually take decades to uncover and are unlikely to occur under short-term funding schemes. Outside grants are also in increasingly short supply: young scientists enter the workforce at a faster rate than older scientists retire. Some of our respondents said that the vicious competition for funds can influence their work. Funding "affects what we study, what we publish, the risks we (frequently don't) take," explains Gary Bennett a neuroscientist at Duke University. It "nudges us to emphasize safe, predictable (read: fundable) science." Truly novel research takes longer to produce, and it doesn’t always pay off. A National Bureau of Economic Research paper found that, on the whole, truly unconventional papers tend to be less consistently cited in the literature. So scientists and funders increasingly shy away from them, preferring short-turnaround, safer papers. But everyone suffers from that: the NBER report found that novel papers also occasionally lead to big hits that inspire high-impact, follow-up studies. "I think because you have to publish to keep your job and keep funding agencies happy, there are a lot of mediocre scientific papers out there ... with not much new science presented. Another worry: When independent, government, or university funding sources dry up, scientists may feel compelled to turn to industry or interest groups eager to generate studies to support their agendas. Already, much of nutrition science, for instance, is funded by the food industry — an inherent conflict of interest. And the vast majority of drug clinical trials are funded by drugmakers. Studies have found that private industry–funded research tends to yield conclusions that are more favorable to the sponsors. Finally, all of this grant writing is a huge time suck, taking resources away from the actual scientific work. Many professors spend 50 percent of their time writing grant proposals. Imagine what they could do with more time to devote to teaching and research? It’s easy to see how these problems in funding kick off a vicious cycle. To be more competitive for grants, scientists have to have published work. To have published work, they need positive results. That puts pressure on scientists to pick "safe" topics that will yield a publishable conclusion — or, worse, may bias their research toward significant results. The current system is in perpetual disequilibrium, because it will inevitably generate an ever-increasing supply of scientists vying for a finite set of research resources and employment opportunities.One straightforward way to ameliorate these problems would be for governments to simply increase the amount of money available for science. (Or, more controversially, decrease the number of PhDs, but we’ll get to that later.) If Congress boosted funding for the National Science Foundation, that would take some of the competitive pressure off researchers. But that only goes so far. Funding will always be finite, and researchers will never get blank checks to fund the risky science projects of their dreams. So other reforms will also prove necessary. The obvious solution is to simply make [scientific funding] a stable program, with an annual rate of increase tied in some manner to inflation. *BITTER COMPETITION LEADS TO GROUP LEADERS WORKING DESPERATELY TO GET ANY MONEY JUST TO AVOID CLOSING THEIR LABS, SUBMITTING MORE PROPOSALS, OVERWHELMING THE GRANT SYSTEM FURTHER. IT'S ALL KINDS OF VICIOUS CIRCLES ON TOP OF EACH OTHER..* Alternatively, researchers in the journal *mBio* recently called for a lottery-style system. Proposals would be measured on their merits, but then a computer would randomly choose which get funded. "Although we recognize that some scientists will cringe at the thought of allocating funds by lottery," the authors of the *mBio* piece write, "the available evidence suggests that the system is already in essence a lottery without the benefits of being random." Based on our survey, funding appears to be at the root of many of the problems facing scientists, and it’s one that deserves more careful discussion.

Too many studies are poorly designed. Blame bad incentives. Scientists are ultimately judged by the research they publish. And the pressure to publish pushes scientists to come up with splashy results, of the sort that get them into prestigious journals. The problem here is that truly groundbreaking findings simply don’t occur very often, which means scientists face pressure to game their studies so they turn out to be a little more "revolutionary." Some of this bias can creep into decisions that are made early on: choosing whether or not to randomize participants, including a control group for comparison, or controlling for certain confounding factors but not others. Many of our survey respondents noted that perverse incentives can also push scientists to cut corners in how they analyze their data. A recent study found "an epidemic" of statistical significance: 96 percent of the papers boasted statistically significant results. That seems awfully suspicious. It suggests the biomedical community has been chasing statistical significance, potentially giving dubious results the appearance of validity — simply suppressing important results that don't look significant enough. Fewer studies share effect sizes (which arguably gives a better indication of how meaningful a result might be) or discuss measures of uncertainty. The current system has done too much to reward results. This causes a conflict of interest: The scientist is in charge of evaluating the hypothesis, but the scientist also desperately wants the hypothesis to be true. The consequences are staggering. As much as 30% of the most influential original medical research papers later turn out to be wrong or exaggerated. Our respondents suggested that the two key ways to encourage stronger study design — and discourage positive results chasing — would involve rethinking the rewards system and building more transparency into the research process. "I would make rewards based on the rigor of the research methods, rather than the outcome of the research," writes Simine Vazire, a journal editor and a social psychology professor. "Grants, publications, jobs, awards, and even media coverage should be based more on how good the study design and methods were, rather than whether the result was significant or surprising."

We've gotten used to working away in private and then producing a sort of polished document in the form of a journal article. This tends to hide a lot of the thought process that went into making the discoveries. We'd like attitudes to change so people focus less on the race to be first to prove a particular theorem, or in science to make a particular discovery, and more on other ways of contributing to the furthering of the subject. When it comes to published results, meanwhile, many of our respondents wanted to see more journals put a greater emphasis on rigorous methods and processes rather than splashy results. One thing that would have the biggest impact is removing publication bias: judging papers by the quality of questions, quality of method, and soundness of analyses, but not on the results themselves. Some journals are already embracing this sort of research. *PLOS One*, for example, makes a point of accepting negative studies (in which a scientist conducts a careful experiment and finds nothing) for publication, as does the aptly named Journal of Negative Results in Biomedicine. More transparency would also help: ClinicalTrials.gov allows researchers to register their study design and methods ahead of time and then publicly record their progress. That makes it more difficult for scientists to hide experiments that didn't produce the results they wanted. (The site now holds information for more than 180,000 studies in 180 countries.) Some drug companies and universities have created portals that allow researchers to access raw data from their trials. The key is for this sort of transparency to become the norm rather than a laudable outlier.

Replicating results is crucial. But scientists rarely do it. Replication is another foundational concept in science. Researchers take an older study that they want to test and then try to reproduce it to see if the findings hold up. Testing, validating, retesting — it's all part of a slow and grinding process to arrive at some semblance of scientific truth. But this doesn't happen as often as it should, our respondents said. Scientists face few incentives to engage in the slog of replication. And even when they attempt to replicate a study, they often find they can't do so. Increasingly it's being called a "crisis of irreproducibility." As for the underlying causes, our survey respondents pointed to a couple of problems. First, scientists have very few incentives to even *try* replication: funding agencies prefer to support projects that find new information instead of confirming old results. Journals are also reluctant to publish replication studies unless they contradict earlier findings or conclusions. The result is to discourage scientists from checking each other's work. The second problem is that many studies can be difficult to replicate. Sometimes, as we saw in the previous section, the study is simply poorly designed or outright wrong. Scientists need more carrots to entice them to pursue replication in the first place. The next step would be to make replication of studies easier. This could include more robust sharing of methods in published research papers.

Peer review is broken. Peer review is meant to weed out junk science before it reaches publication. Yet over and over again in our survey, respondents told us this process fails. It was one of the parts of the scientific machinery to elicit the most rage among the researchers we heard from.

Normally, peer review works like this: A researcher submits an article for publication in a journal. If the journal accepts the article for review, it's sent off to peers in the same field for constructive criticism and eventual publication — or rejection. But numerous studies have shown that peer review doesn't reliably prevent poor-quality science from being published. It's not always easy to find the best people to peer-review manuscripts in the field, researchers delay doing the work (leading to publication delays of up to two years), and that when they finally do sit down to peer-review an article they might be rushed and miss errors in studies. That's not to mention the problem of peer review bullying. Since the default in the process is that editors and peer reviewers know who the authors are (but authors don't know who the reviews are), biases against researchers or institutions can creep in, opening the opportunity for rude, rushed, and otherwise unhelpful comments. On the question of bias and transparency, our respondents were surprisingly divided. Several suggested that all journals should move toward double-blinded peer review, whereby reviewers can't see the names or affiliations of the person they're reviewing and publication authors don't know who reviewed them. The main goal here was to reduce bias. Yet others thought that more transparency, rather than less, was the answer: "While we correctly advocate for the highest level of transparency in publishing, we still have most reviews that are blinded, and I cannot know who is reviewing me," writes Lamberto Manzoli, a professor of epidemiology and public health. "Too many times we see very low quality reviews, and we cannot understand whether it is a problem of scarce knowledge or conflict of interest." Perhaps there is a middle ground. For example, eLife, a new open access journal that is rapidly rising in impact factor, runs a collaborative peer review process. Editors and peer reviewers work together on each submission to create a consolidated list of comments about a paper. The author can then reply to what the group saw as the most important issues, rather than facing the biases of individual reviewers. Other respondents argued that we might need to radically rethink the entire process of peer review from the ground up. Some respondents wanted to think of peer review as more of a continuous process, in which studies are repeatedly and transparently updated and republished as new feedback changes them — much like Wikipedia entries. One possible model already exists in mathematics and physics, where there is a long tradition of "pre-printing" articles. Studies are posted on an open website called arXiv.org, often before being peer-reviewed and published in journals. There, the articles are sorted and commented on by a community of moderators, providing another chance to filter problems before they make it to peer review. The bottom line is that traditional peer review has never worked as well as we imagine it to — and it's ripe for serious disruption.

Too much science is locked behind paywalls. After a study has been funded, conducted, and peer-reviewed, there's still the question of getting it out so that others can read and understand its results.

Over and over, our respondents expressed dissatisfaction with how scientific research gets disseminated. Too much is locked away in paywalled journals, difficult and costly to access. Some respondents also criticized the publication process itself for being too slow, bogging down the pace of research.

On the access question, a number of scientists argued that academic research should be free for all to read. A single article in *Science* will set you back $30; a year-long subscription to *Cell* will cost $279. There are 2,000 journals that can cost up to $10,000 or $20,000 a year for a subscription. *IT'S OVERLY SIMPLISTIC TO COUNT UP SOMEONE'S PAPERS AS A MEASURE OF THEIR WORTH.* Many US institutions pay those journal fees for their employees, but not all scientists (or other curious readers) are so lucky. Taxpayers pay for research at government labs and universities but do not usually have access to the results of these studies, since they are behind paywalls of peer-reviewed journals. Many of our respondents urged their peers to publish in open access journals. But career advancement can often depend on publishing in the most prestigious journals, like *Science*or *Nature*, which still have paywalls. There's also the question of how best to finance a wholesale transition to open access.After all, journals can never be entirely free. Someone has to pay for the editorial staff, maintaining the website, and so on. Right now, open access journals typically charge fees to those submitting papers, putting the burden on scientists who are already struggling for funding. However, many scientists are going a much simpler route: illegally pirating papers. Millions of researchers around the world now use Sci-Hub, a site set up by Alexandra Elbakyan, a Russia-based neuroscientist, that illegally hosts more than 50 million academic papers. One respondent had an even more radical suggestion: that we abolish the existing peer-reviewed journal system altogether and simply publish everything online as soon as it’s done.

Science is poorly communicated to the public. Quite a few respondents in our survey expressed frustration at how science gets relayed to the public. They were distressed by the fact that so many laypeople hold on to completely unscientific ideas or have a crude view of how science works. They have a point. Science journalism is often full of exaggerated, conflicting, or outright misleading claims. If you ever want to see a perfect example of this, check out "Kill or Cure," a site where Paul Battley meticulously documents all the times the Daily Mail reported that various items — from antacids to yogurt — either cause cancer, prevent cancer, or sometimes do both. Other respondents pointed out that scientists themselves often oversell their work, even if it's preliminary, because funding is competitive and everyone wants to portray their work as big and important and game-changing. Opinions differed on how to improve this sorry state of affairs — some pointed to the media, some to press offices, others to scientists themselves. Plenty of our respondents wished that more science journalists would move away from hyping single studies. On a given subject, there are often dozens of studies that examine the issue. It is very rare for a single study to conclusively resolve an important research question, but many times the results of a study are reported as if they do. Still other respondents noted that scientists themselves should spend more time learning how to communicate with the public — a skill that tends to be under-rewarded in the current system. Being able to explain your work to a non-scientific audience is just as important as publishing in a peer-reviewed journal, but currently the incentive structure has no place for engaging the public.

Life as a young academic is incredibly stressful. When we asked researchers what they'd fix about science, many talked about the scientific process itself, about study design or peer review. These responses often came from tenured scientists who loved their jobs but wanted to make the broader scientific project even better. But on the flip side, we heard from a number of researchers — many of them graduate students or postdocs — who were genuinely passionate about research but found the day-to-day experience of being a scientist grueling and unrewarding. Today, many tenured scientists and research labs depend on small armies of graduate students and postdoctoral researchers to perform their experiments and conduct data analysis. These grad students and postdocs are often the primary authors on many studies. In a number of fields, such as the biomedical sciences, a postdoc position is a prerequisite before a researcher can get a faculty-level position at a university. This entire system sits at the heart of modern-day science. But these low-level research jobs can be a grind. Postdocs typically work long hours and are relatively low-paid for their level of education, they tend to be hired on for one to three years at a time, and in many institutions they are considered contractors, limiting their workplace protections. We heard repeatedly about extremely long hours and limited family leave benefits. Oftentimes this is problematic for individuals in their late 20s and early to mid-30s who have PhDs and who may be starting families while also balancing a demanding job that pays poorly. This lack of flexibility tends to disproportionately affect women — especially women planning to have families — which helps contribute to gender inequalities in research. There is very little support for female scientists and early-career scientists. Because universities produce so many PhDs but have way fewer faculty jobs available, many of these postdoc researchers have limited career prospects. Some of them end up staying stuck in postdoc positions for five or 10 years or more. In the biomedical sciences each available faculty position receives applications from hundreds or thousands of applicants, putting immense pressure on postdocs to publish frequently and in high impact journals to be competitive enough to attain those positions. Some respondents also noted that workplace issues for grad students and postdocs were inseparable from some of the fundamental issues facing science that we discussed earlier. The fact that university faculty and research labs face immense pressure to publish — but have limited funding — makes it highly attractive to rely on low-paid postdocs. Young researchers are highly trained but relatively inexpensive sources of labor for faculty. The core point underlying all the suggestions was that universities and research labs need to do a better job of supporting the next generation of researchers. Indeed, that's just as important as addressing problems with the scientific process itself. Young scientists, after all, are by definition the future of science.

Science is not doomed. For better or worse, it still works. Look no further than the novel vaccines or the discovery of gravitational waves. But science is conducted by fallible humans, and it hasn’t been human-proofed to protect against all our foibles. To that end, here are some broad suggestions. Science has to acknowledge and address its money problem. Science is enormously valuable and deserves ample funding. Science needs to celebrate and reward failure. Accepting that we can learn more from dead ends in research and studies that failed would alleviate the "publish or perish" cycle. It would make scientists more confident in designing robust tests and not just convenient ones, in sharing their data and explaining their failed tests to peers, and in using those null results to form the basis of a career (instead of chasing those all-too-rare breakthroughs). Science has to be more transparent. Scientists need to publish the methods and findings more fully, and share their raw data in ways that are easily accessible for those who may want to reanalyze or replicate their findings.

Adapted from Vox

<u>Exercise III</u>.

Fill in the gaps.

1) How is the New York Times doing with the new digital ______________ it put up last March?

2) A lot of the complaints are about things that ______________ the mobile elite elsewhere.

3) Parliament cannot write laws that leave no possibility of ________________ consequences.

4) Employers have little ________________ to raise pay when the unemployment rate is high.

5) A new experiment will soon test the gene study's results in a more _______________ way.

6) The board decided last week not to renew the license, which will ______________ Nov. 30.

7) Marriage, motherhood, and family life, she says, are the __________________ female dream.

8) Keep informed of new developments and _______________ the information as necessary.

9) The _________________, however, is experimental data like that obtained in the study.

10) The only way to ________________ the pressure is to insert a tube or shunt to drain it

Exercise IV.

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

to shy away, elegant and objective, to afflict, to hijack, to riddle, to hail, to expire, to vie, to cringe, to entice

Exercise V.

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

to sustain	strong and healthy
to contribute	a substance used to stimulate the production of antibodies and provide immunity against one or several diseases, prepared from the causative agent of a disease, its products, or a synthetic substitute, treated to act as an antigen without inducing the disease
opaque	never ending or changing
antacid	capable of making mistakes
fallible	make (suffering, deficiency, or a problem) less severe
perpetual	give (something, esp. money) in order to help achieve or provide something
vaccine	required as a prior condition

to alleviate	support physically or mentally
robust	not able to be seen through; not transparent
prerequisite	preventing or correcting acidity, esp. in the stomach

Exercise VI.

Identify the part of speech the words belong to: rigorous, bureau, inherent, aptly, laudable, semblance, slog, tenure

Exercise VII.

Match the words to make word combinations:

outside	equipment
starting	results
perennial	student
lab	communities
money	grants
English-speaking	gripe
wide	problem
graduate	variety
scientific	point
positive	poll

Exercise VIII.

Summarize the article "The biggest problems facing science, according to 270 scientists".

2. Why trees don't ungrow

Exercise I.

Say what Russian words help to guess the meaning of the following words: cliché, thermodynamics, natural, biology, perspective, physicist, fundamental, collections, physics, monster,

Exercise II.

Make sure you know the following words and word combinations.
sweeping, shoot, crisp, to bath, averse, clump, staggering, dizzying, shatter, starch

Why trees don't ungrow

The cliché that life transcends the laws of thermodynamics is completely wrong. The truth is almost exactly the opposite

Living things are so impressive that they've earned their own branch of the natural sciences, called biology. From the perspective of a physicist, though, life isn't different from non-life in any fundamental sense. Rocks and trees, cities and jungles, are all just collections of matter that move and change shape over time while exchanging energy with their surroundings. Does that mean physics has nothing to tell us about what life is and when it will appear? Or should we look forward to the day that an equation will finally leap off the page like a mathematical Frankenstein's monster, and say, once and for all, that this is what it takes to make something live and breathe? As a physicist, I prefer to chart a course between reductionism and defeat by thinking about the probability of matter becoming more life-like. The starting point is to see that there are many separate behaviours that seem to distinguish living things. They harvest energy from their surroundings and use it as fuel to make copies of themselves, for example. They also sense, and even predict things about the world they live in. Each of these behaviours is distinctive, yes, but also limited enough to be able to conceive of a non-living thing that accomplishes the same task. Although fire is not alive, it might be called a primitive self-replicator that 'copies' itself by spreading. Now the question becomes: can physics improve our understanding of these life-like behaviours? And, more intriguingly, can it tell us when and under what conditions we should expect them to emerge? Increasingly, there's reason to hope the answer might be yes. The theoretical research I do with my colleagues tries to comprehend a new aspect of life's evolution by thinking of it in thermodynamic terms. When we conceive of an organism as just a bunch of molecules, which energy flows into, through and out of, we can use this information to build a probabilistic model of its behaviour. From this perspective, the extraordinary abilities of living things might turn out to be extreme outcomes of a much more widespread process going on all over the place, from turbulent fluids to vibrating crystals – a process by which dynamic, energy-consuming structures become fine-tuned or adapted to their environments. Far from being a freak event, finding something akin to evolving lifeforms might be quite likely in the kind of universe we inhabit – especially if we know how to look for it. The understanding that life and heat are intertwined is very old knowledge. Moses, for one, was launched into his first encounter with the Creator of all life by the sight of a tree ablaze, burning with a marvellous fire that left the living organism unscathed. In physics, heat is a form of energy, made up of the random movements and collisions of molecules as they bounce off each other at the nanoscale. Much of the world's energy is tied up as heat. Although it sounds like something that just wobbles around in the background as other factors take centre stage, it actually plays a crucial role in making some of the most interesting kinds of behaviour possible. In particular, we'll see that heat and time are bound together in an intricate dance, and the release of heat is what stops time going backwards. Some things in the world seem reversible: I can kick a ball upward and it will rise, or I can drop a ball from a height, and it will fall. Putting it this way just seems like common sense, but it turns out that this pairing of dynamical trajectories, where one path looks like the time-reversed movie of the other, is a symmetry built into the basic mathematical structure of Newton's laws. Anything that can go one way can go the other, if you just set it moving back the way it came. As a consequence, the most 'normal' thing in physics would be for events to be able to reverse themselves in time, just like the ball that goes up and then down. We don't immediately grasp the sweeping significance of time-reversal symmetry because a whole lot of what we see doesn't seem to have this property. Little green shoots soak up the Sun and grow into mighty trees, but we never see a full-grown pine 'ungrow' itself into a cone buried in the dirt. Sandcastles disintegrate under the waves, but we never see them splash back together when the tide recedes. Countless examples of ordinary occurrences around us would look extraordinary if they happened in rewind. The 'arrow of time' seems to point in one direction, but there's no obvious reason in principle to think it should. So what's going on? The short answer is that we're not looking closely enough. When a piece of wood burns, an enormous amount of heat and chemical product is exchanged with the surrounding air. In order to run the tape backwards and spontaneously generate wood from ash and anti-flame, we'd have to somehow give every little molecule in the ash and atmosphere a backwards push to send it bouncing along the reverse track. That is not going to happen. Many scientific commentators have noted the connection between heat and the arrow of time. However, only in the past 20 years or so have physicists developed a crisp, comprehensive formulation of the relationship. One of the most important contributions came from a theorist named Gavin Crooks. He asked the following question: given that I have a movie (say, of a piece of wood burning to ash or a plant growing) and the rewind version of that movie, how would I tell which one is more likely to happen? By applying some basic assumptions, he was able to mathematically prove the following. If you have a system (a piece of wood or a plant, for example) surrounded by a 'bath' of randomly jiggling particles (say, the atmosphere), the more heat the system releases into its bath, the less likely it is to rewind itself. In a rigorous, quantitative sense, the dissipation of heat is the price we pay for the arrow of time. Why? Another way of phrasing this insight is to note that the more a system increases the entropy of its surroundings, the more irreversible it becomes. Now, it must be said that in the grand contest for the most misunderstood idea in the history of physics, entropy is probably the winner. Even people who are normally averse to any mention of the natural sciences will sagely volunteer that entropy – read: messiness, dysfunction, chaos, disorder, who knows? – must increase, all the time. It's the second law of thermodynamics, obviously. But this simple picture can't be right. Living organisms, for one, seem to defy this misleading gloss on the second law. They take disorganised bits and pieces of matter, and put them together in fiendishly complex and refined ways. Thankfully, the full story is substantially more nuanced. Connoisseurs use entropy in a technical, microscopic sense, as a statistical measure of the number of different ways the same kind of arrangement of matter can be constructed out of its constituent parts. For a room full of air, for example, it turns out there are just many, many more ways of spreading out the molecules uniformly than there are of squishing them into clumps. That's why uniform air density wins the entropic game, and nature abhors a vacuum. The particles diffuse themselves evenly because that's just the most likely thing to happen over time. The connection between entropy and heat is more subtle. Remember that heat is energy diffused randomly among the particles in a substance. The more energy, the more ways of sharing it around; and the more ways of sharing the energy around, the higher the entropy. Back to Crooks's example of a system in a bath, then, the more heat a system releases, the more it increases the entropy of its surroundings – and, as Crooks showed, the less likely it is that this sequence of events could rewind itself.

This is what the second law means: the reason a heat-producing movie is more likely than its heat-absorbing re-run has to do with the number of ways you can disperse that heat in the surrounding bath. The more heat you throw into the bath, the less hope you have of getting it back from a freak fluctuation, and the less likely it is that you will have the energy you need to retrace your steps once the movie has run forward. It's like releasing a bagful of feathers into a gusting wind and hoping to catch them with a net. If you only release one feather, the gale might blow it back to you; but if you release hundreds or thousands, the chance of capturing them all is basically nil. Now we can bring life into the picture. Living things clearly have energy to burn, and they get this energy from being worked on. Like heat, 'work' in thermodynamics involves units of energy. But instead of the uncoordinated wiggling of molecules, here it's a measure of how much and how fast energy has been transferred to a system from its surroundings in a way that produces a change. There are a variety of versions, such as movement, volume change and chemical transformation. What unites these processes is that energy is being forced, pushed or driven into a system from the outside, in a way that modifies the system's shape or location. When you hit a car, it might move, or you might dent it, or both. In any case, you've done work on it. Life is superb at capturing energy through work. Growing a plant means doing work on it, no less than when we put shoulder to yoke and drag a cart up a hill. In these situations the conservation of energy required by Newton's laws implies one of two things: either all the energy put in as work stays stored in the system; or else it's released into the surroundings as heat. Recall, too, what we said before about the release of heat and time-reversal symmetry. So the question of how much work gets done, and when, makes all the difference to which events are more or less likely in the movie we're watching.

Now we know why mighty trees don't ungrow themselves: because life produces heat. From a physics perspective, a tree harvests energy from its surroundings – work is done on it – and in the process, it dissipates energy to the surrounding air as heat. The differences in probability between forward and reverse in such cases are staggering. Suffice it to say, once the work gets flowing (and dissipating), backwards movies usually cease to be worth even talking about. With a few tricks of algebra, you can use Crooks's equation to compare the likelihoods of two future events in a system that's being pushed by external forces and surrounded by a bath of randomly jiggling molecules. That includes the plant growing in the air, and anything that's alive, in fact. So, if I zap a chemical mixture with electric shocks, or mechanically vibrate the container of a viscous fluid – does thinking about work and heat help me to predict if something resembling life might eventually emerge, after some energy has been allowed to flux through the system? Perhaps, but with a twist. To probe the implications of work for how life (and evolution) evolved, a more versatile analogy is required. Let's imagine a battery-powered car, exploring a rugged mountain range. Mathematically, the car's location can be thought of as corresponding to the full microscopic configuration of a system composed of many different particles. Every spot on the terrain that the car might be, we can think of as a unique and different way of arranging all the molecular building blocks of some larger object. Accordingly, we have to think of the car not as having four cardinal directions to drive in, but rather, 1025 or more! And somewhere, out on that vast sierra, there's a spot that represents a bacterium, a plant, a cat. At any given moment, our car is furiously spinning its wheels, winding its way slowly up over a narrow pass, or bouncing rapidly down into another ravine. From time to time, the car randomly swerves and changes direction. This is a reasonable metaphor for a system that undergoes changes in energy, but doesn’t experience external drives that do work on it. Sometimes, the car goes uphill; this corresponds to our system absorbing heat and storing the energy. Sometimes, the car goes downhill, which we’d liken to the clown popping out of the box as the spring is released. So where does the exploring car end up? Both intuition and a more rigorous treatment of the physics tell us that two basic factors are going to affect what happens. First, the car is more likely to drive to places that are close to its starting point, and separated from that point by relatively flat terrain. Second, it will tend to go downhill more than it tends to go uphill. After a very long time, we might expect the car to wander so much that we’d have no idea where it was at the beginning – but its avoidance of hilltops and preference for valleys would probably remain.

To bring work into the picture, we just need to give the car a solar panel. This makes its wheels spin more vigorously when it’s positioned and angled so that the Sun is brightest. Now the rules of thumb for how the car explores are going to get dramatically more complicated. All things being equal, we’d still expect the car to stay close to home, go downhill, and avoid rugged terrain (at least until it gets stuck). In addition, we now have to think about the places and times that the car will get a power-boost from the Sun overhead. There are going to be cases where the car can more readily traverse a sunny hill than a shady plain, because of the extra help it gets by staying in the bright spots. Given enough time, we can no longer be confident that we'll find the car in some deep valley near home base; instead, we have to think about how far and how fast it might have travelled if it found a path on which the Sun kept shining. Described in this way, the vehicle's dynamics are affected by a dizzying variety of factors, and there are many more possibilities for where the mountain-rover might go. The solar-powered mountain-rover metaphor helps us to think about the evolution of a very diverse range of work-absorbing systems. Of course, the prospect of sifting through such a vast space of possibilities and landing on life at first seems hopeless. But things look different once we ask a simple question, namely: what determines which places are sunny, and which places aren't? At least part of the answer comes from the peculiarities of how a system's structure allows it to connect with its surrounding energy source. Children often notice that a wineglass will ring at a different pitch depending on how much water is poured into it. A different, but related observation is that vessels made from the same amount of glass, and filled with the same amount of water, can ring at different pitches depending on their shape. What this reveals is that the way matter is arranged can significantly affect how it tends to move and vibrate. Not only that, but the details of such an arrangement also change how matter absorbs work energy from its surroundings. Think of an opera singer who shatters a goblet with the perfect pitch of her song, due to a phenomenon known as resonance. Here, because the glass tends to vibrate at a frequency that is well-matched to the frequency of the sound, the oscillations in the glass produced by the energy in the sound waves are violent enough to break it.

We encounter the work-absorbing peculiarities of how matter is arranged all around us: from the ways pigment molecules absorb and scatter light so that we perceive them as having colours, to the fact that we can digest and be nourished by the starch in a potato more than by the cellulose in a bale of hay. From the perspective of chemical physics, a human being's inability to eat grass is just about how the atoms that comprise a person's digestive system are arranged. If these same carbons, nitrogens, oxygens and so on were re-fashioned into a cow stomach, the chemical work stored in grass would be ours for the taking. It's when we take this idea back to our solar-powered rover that things get interesting. Suppose we start with a collection of chemical building blocks in a thrown-together, uninteresting structure. That corresponds to parachuting the car into a randomly chosen starting location in the mountain range. But now, suppose that we subject these chemical building blocks to a challenging external environment – to a collection of energy sources that are accessible in principle, but only available in practice when the chemicals are arranged in rare, specially-matched shapes that happen to solve the problem of how to absorb work. For the rover, which we have said has unimaginably many possible directions to drive in, the challenging environment manifests as a landscape that's mostly not very sunny, except when you are driving in just the right direction, in the right place, at the right time. Sure, it's still not easy to tell where the rover must go in general. But there are particular scenarios where the matters become significantly clearer. We might think of a case in which the rover starts off in a sunny spot, spins its wheels furiously, and speeds to a new place in the shade, where its wheels grind mostly to a halt. Having been carried irreversibly to a new place by the absorption and dissipation of work, it then gets stuck in a shape that is bad at absorbing energy. That's roughly equivalent to the opera singer shattering the goblet. At the beginning, the glass resonates and absorbs a lot of work from the song, which gets largely dissipated as heat when the glass shatters and settles into an inert heap of shards. Once in this state, the shards no longer resonate, and the rate of work absorption drops significantly. We can also envision the opposite scenario. Suppose we have a single bacterium sitting in a big jar of food and oxygen. After 20 minutes or so, we should have two bacteria, and 20 minutes later gets us two more. What we expect to see, in the short term, is a process of exponential population growth. Individual bacteria harness the chemical work available in their surroundings, and pay the thermodynamic cost of making copies of themselves. Since the number of bacteria is growing, the rate of work absorption is also constantly increasing – at least until the food runs out and the party stops. We can liken this process to a rover that gets a bit of sunshine, which helps it edge its way a bit further out of the shade, so that its wheels speed up even more and carry it to an ever-sunnier location over time. The system in this case exhibits a sustained, self-reinforcing process that grows its ability to absorb work from the environment. Note that there's nothing in this thermodynamic description of reproduction that specifically picks out the notion of a discrete entity (such as a bacterium) reproducing itself. Rather, self-replication is just one example of a more general class of processes that exhibit what we call positive feedback. Positive feedback can happen whenever there's a quantity in a system whose increase brings about a rise in its own rate of growth. In the case of self-replicating cells, the quantity in question is the number of cells itself: a larger number of cells can make more cells faster. However, one can also envision self-reinforcing behaviours that have to do with the shape or arrangement of a system as a whole; and in that case, the exploring rover story remains the same as ever. Looking at life this way allows us to recognise a similar feedback signature in cases where no self-copying self is apparent. Just to recap where we've travelled. Living things manage not to fall apart as fast as they form because they constantly increase the entropy around them. They do this because their molecular structure lets them absorb energy as work and release it as heat. Under certain conditions, this ability to absorb work lets organisms (and other systems) refine their structure so as to absorb more work, and in the process, release more heat. It all adds up to a positive feedback loop that makes us appear to move forward in time, in accordance with the extended second law. This process takes on a special significance in a setting like that of the vibrating glass. Here, the environmental energy source presents a particular challenge, such that the system (the glass) can only absorb energy if it adopts the right shapes. That's equivalent to our rover finding that rare sliver of sunlight and managing to drive in just the right way to stay in the bright spots. If something about the system's configuration lets it use the absorbed energy to power a feedback loop in a challenging scenario, you end up with a recipe for a system that evolves over time into more and more finely-tuned, specialised, energy-absorbing shapes. If you leave a lump of glass in the presence of a soprano for long enough, the shape it ultimately takes should depend on the precise pitch(es) she chooses to sing at.

In my research group's first theoretical papers on this subject, we have referred to this mechanism of self-organisation as dissipative adaptation.Recently, we conducted two tests of the idea with computer simulations. In one study, we took a mixture of simple dots or points floating in viscous fluid. To make the environment more challenging, we imposed a simple rule: each pair of points was connected by a stretchy spring, which could randomly hook or unhook when close together. We then took one of the points amongst a group of 20 of them and pushed on it with an oscillating force of a single frequency. What we saw next was intriguing. As the springs randomly hooked and unhooked, a specific network of tangled connections formed. These connections tended to vibrate at the frequency of the external force – hence they absorbed an exceptionally large amount of energy. Alternatively, when we engineered it so that the springs snapped more readily when stretched, we saw the opposite effect, like the opera singer's shattered glass: a network formed that was attuned to not vibrate at that frequency. That is, the points adapted their shape to not absorbing energy. We got similar results in a second study. Here we put an initially randomly arranged collection of atoms in the presence of a rich but challenging source of energy that could only be accessed by a special combination of those atoms. After letting the atoms react for a long time, the composition of chemicals was biased to be either unusually bad or extremely good at extracting energy. In other words, the system exhibited a tendency to find and stay stuck in states that look adapted to their environment. In both these cases, the point is not that all matter everywhere is trying to absorb and dissipate more energy all the time; nor is it that the second law of thermodynamics is magically guiding the discovery of organised structures that are better at increasing entropy. Rather, when particles interact under the challenging conditions created by an energy source, their resulting shapes tend to be fine-tuned to that energy source – even without the help of self-replication and natural selection. As it happens, living things are both marvellously complex and breathtakingly good at meeting the challenges of their environments. We know this is because the life we see today has inherited many of the structural and behavioural adaptations that proved so useful to previous generations. In the biological context, ‘usefulness’ is that which enables survival and self-reproduction. But what’s beginning to emerge from some of this thermodynamic thinking – and what a few of us are eagerly exploring in simulation and experiment – is the possibility that some of the distinctively life-like specialness of how organisms are organised, and which allows them to eat and survive and reproduce, might be recognisable in a broader physical class of systems that do not contain self-copying selves. Instead, they are propelled towards strikingly special shapes by the thermodynamic laws governing positive feedback in the presence of a challenging energy source. This process might explain how evolution can get going in inert matter. Whether this will ultimately make a big or small difference in how we understand living things at the microscopic level, we don’t know. There’s still more work to be done. But what our new vantage point on thermodynamics reveals is that a great many uncharted, and seemingly random, explorations of shape and form have a surprisingly good chance of ending up somewhere interesting – perhaps even the summit of the very distant mountaintop that we occupy on that unimaginably huge terrain, with a tiny flag reading ‘humanity’.

Adapted from Aeon

Exercise III.

Fill in the gaps.

1) In the meantime, ________________ in physics has never been more firmly established.

2) She knows that a low flame burns longer and more ________________ than a high blaze.

3) It's this inability to ________________ of alternative approaches that leads to despair.

4) Each of these seven aspects interact and ________________ as individuals interpret events.

5) Giant gas clouds have been found close enough to home to keep the galaxy ________________.

6) Buildings came through the blow ______________ and vegetation suffered only slightly.

7) Obviously, he had forgotten about his _____________, pre-planned programme that day.

8) Increasing its concentration, however, would make the gel impractically ________________.

9) So Chu's method improves the precision of the more _____________ optical microscope.

10) _______________, a crystalline polymer derived from glucose, constitutes about 41-43%.

Exercise IV.

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

to leap off, to conceive, to launch, to wobble, intricate, to recede, to giggle, to wiggle, to grind, to recap

Exercise V.

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

intertwine	extremely good or splendid
cellulose	moving unsteadily or violently
marvelous	wind (a tape or film) back to the beginning
turbulent	twist or twine together
vigorously	a place or position affording a good view of something
inert	an insoluble substance that is the main constituent of plant cell walls and of vegetable fibers such as cotton. It is a polysaccharide consisting of chains of glucose monomers
rewind	having a thick, sticky consistency between solid and liquid
discrete	chemically inactive
vantage	in a way that involves physical strength, effort, or energy
viscous	individually separate and distinct

Exercise VI.

Identify the part of speech the words belong to.

reductionism, intriguingly, intricate, rigorous, dissipation, fiendish, fluctuation, versatile, pigment, harness

Exercise VII.

Match the words to make word combinations:

vibrating	outcomes
probabilistic	fluids
extreme	crystals
turbulent	monster
thermodynamic	sciences
theoretical	model
harvest	things
Frankenstein’s	terms
natural	research
living	energy

Exercise VIII.

Summarize the article “Why trees don’t ungrow”.

3. Universe in a bubble

Exercise I.

Say what Russian words help to guess the meaning of the following words: cosmic, reality, history, interesting, student, modern, diameter, telescope, methods, distance.

Exercise II.

Make sure you know the following words and word combinations.
Supernova, lamppost, to permeate, to endow, appreciably, to percolate, to spawn, deceleration, luminosity, filament

Universe in a bubble

Maybe we don't have to speculate about what life is like inside a bubble. It might be the only cosmic reality we know

My history with bubble universes began in 1968 when I met Robert Kirshner while we were both undergraduates at Harvard in Massachusetts. He was a lively, funny, interesting fellow. We met up again a few years later, when he was a graduate student at Caltech in California and I was a new postdoc there. At Caltech, he had a piece of good luck that changed the direction of his career and, ultimately, helped reshape modern cosmology. While he was at Caltech, a bright supernova (an exploding star ending its life) became visible, and Kirshner was able to study it using the huge 200-inch-diameter Hale telescope on Palomar Mountain. Combining his findings with some innovative contemporary methods, he developed a clever way to measure its distance. The distance scale of the Universe was poorly known at the time, and getting more accurate numbers was critical to developing a better understanding of cosmic structure and evolution. Beginning in the mid-1990s, now as a member of Harvard's faculty, Kirshner started a group using supernovae to measure the expansion rate of the Universe – a particularly telling indication of how the cosmos is changing over time. Astronomers presumed that the expansion had been slowing down ever since the Big Bang, running down due to the gravitational pull between galaxies. The big question was: how quickly was this cosmic deceleration happening? To get an answer, Kirshner and his team measured distances to supernovae near and far away, and compared those distances with their velocities of recession. In essence, they were using supernovae as standard lampposts of known intrinsic luminosity, whose distance you could ascertain from their apparent brightness. Then you could look at how much that light had been stretched (shifted toward the red end of the spectrum) by cosmic expansion, and compare the rate of expansion for supernovae of different distances. Because of the finite velocity of light, the farther out we look, the farther back in time we see. A light-year, about 10 trillion kilometres, is the distance light can travel in a year. If we look out at a distance of 65 million light-years, we would be seeing a supernova that exploded 65 million years ago, when ancient dinosaurs still roamed the Earth. Kirshner was looking back hundreds of millions or even billions of years. A competing team formed at Berkeley in California to perform the same kinds of measurements, using similar techniques. Then things got strange. The two groups found that the expansion of the Universe is not slowing down at all, but speeding up! Kirshner's former students Adam Riess and Brian

Schmidt, as well as Saul Perlmutter at Berkeley, shared the 2011 Nobel Prize in Physics for this discovery. The supernova data indicated that there was something different and unaccounted for in the make-up of our Universe. Those results also suggested something strange about cosmic geometry: the Universe that we know might be just one of many different cosmic bubbles that could live independently – or that could, under certain conditions, interact and even destroy each other.

The explanation for the accelerating cosmic expansion, surprising as it was at first, was readily available from the theoretical toolbox of physicists. It traced back to an idea from Albert Einstein, called the cosmological constant. Einstein invented it in 1917, as part of a failed attempt to produce a static Universe based on his general theory of relativity. At that time, the data seemed to support such a model. In 1922, the Russian mathematician Alexander Friedmann showed that relativity in its simplest form, without the cosmological constant, seemed to imply an expanding or contracting Universe. When Hubble's observations showed conclusively that the Universe was expanding, Einstein abandoned the cosmological constant, but the possibility that it existed never went away.

Then the Belgian physicist Georges Lemaître showed that the cosmological constant could be interpreted in a physical way as the vacuum of empty space possessing a finite energy density accompanied by a negative pressure. That idea might sound rather bizarre at first. We are accustomed, after all, to thinking that the vacuum of empty space should have a zero energy density, since it has no matter in it. But suppose empty space had a finite but small energy density – there's no inherent reason why such a thing could not be possible. Vacuum energy implies negative pressure because of the theory of relativity (special relativity, in this case, which describes the effects of constant motion). The vacuum of empty space should have no intrinsic preferred standard of rest. The crews of two rocket ships passing each other through empty space should each be able to think of themselves as at rest while seeing the other as moving. The only way that different rocket ships passing each other at different speeds could all measure the same value of vacuum energy density is if the vacuum also possessed a negative pressure of equal magnitude. Negative pressure has a repulsive gravitational effect, but at the same time the energy itself has an attractive gravitational effect, since energy is equivalent to mass. (This is the relationship described by E=mc2, another implication of special relativity.) Operating in three directions – left-right, front-back, and up-down – the negative pressure creates repulsive effects three times as potent as the attractive effects of the vacuum energy, making the overall effect repulsive. We call this vacuum energy dark energy, because it produces no light. Dark energy is the widely accepted explanation for why the expansion rate of the Universe is speeding up. By taking careful measurements of supernovae and other indicators, cosmologists can now plot the expansion rate of the Universe accurately as a function of time and, using Einstein's equations of general relativity, determine the value of the vacuum energy. We can also determine the ratio of the pressure to the energy density in dark energy today. That ratio indicates how dark energy changes over time, and how the Universe changes with it. Within the observational uncertainties, the measured value is equal to -1. If it is exactly -1, then the vacuum energy will remain at its current constant value into the far future; 7 x 10-30 grammes per cubic centimetre is a tiny amount of dark energy but it has huge effects across the vastness of space. It is sufficient to cause the visible Universe to double in size in the future every 12.2 billion years: 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1,024 times its current size, and so on.

As far as we know, this doubling could go on forever. Distant galaxies will flee from us because of the stretching of space between us and them. After a sufficient number of doublings, the space between them and us will be stretching so fast that their light will no longer be able to cross this ever-widening gap to reach us. Distant galaxies will fade from view and we will find ourselves seemingly alone in the visible Universe. Vacuum energy is not just a recipe for cosmic loneliness. It could also be an agent of change, destruction and rebirth. The value of vacuum energy depends on the values of different fields permeating empty space. One of these is the Higgs field that endows normal particles with mass; that field is associated with the recently discovered Higgs boson. Nima Arkani-Hamed, a physicist at the Institute for Advanced Study in Princeton, New Jersey, has shown that the Higgs field creates a vacuum state that is unstable on a timescale of 10130 years. If the field decays, it could form bubbles of lower-density vacuum state – a different form of empty space, in essence. 10130 years is a very long time. Our Universe is currently only 13.8 billion years old. Still, the theoretical implications are fascinating. The emergence of altered vacuum-energy states is analogous to boiling water on the stove. Bubbles of lower density (steam) form in the liquid, only in this case the liquid is the ever-inflating sea of dark energy. Another big difference: bubbles of lower density vacuum would expand at nearly the speed of light. An encounter with one of those bubbles would be disruptive, to put it mildly. The value of the Higgs field inside the bubble is different than outside. This means that the masses of the particles in your body would be different inside, too, and therefore the particles in your body would not be able to pass to the inside of the expanding bubble. The bubble wall would hit you and squash you like a bug hit by a car windshield. It would literally be like smashing into a windshield, because light beams are made of massless photons that would not be affected by the change of the Higgs field. They could pass inside the bubble, just as light passes through a glass windshield, whereas the bug does not. Life would be hard inside the bubble, too. Within these bubbles, vacuum energy is large and negative, with a large positive pressure. Because pressure dominates, there is an overall strong gravitational attraction, which has a crushing effect. Any object like Earth that you might imagine forming inside the bubble would be squashed quickly, due to the big overall gravitational attraction of the negative vacuum energy. These bubbles would form with a minuscule radius of about 10-16 centimetres, smaller than the radius of a proton. Inside would be a negative vacuum energy accompanied by a positive pressure. The bubble wall would therefore see a positive pressure inside and a slight negative pressure outside. The positive pressure would push the bubble wall outward, and the slight negative pressure outside would also pull it outward. As a result, the bubble would blow up like a balloon. Within 10-26 seconds or so, it would accelerate to an outward velocity approaching the speed of light.

At that speed, you would have no warning if a bubble wall were about to hit you. Light signals from the bubble wall would not reach you appreciably sooner than the wall itself. You'd feel it pretty much the same moment that you saw it coming. Fortunately, the accelerating expansion of the Universe offers some protection. If a bubble were to form more than 28 billion light-years away from us, its bubble wall would never reach us. That's because the space between us and the bubble is stretching like a rubber band, doubling in size every 12.2 billion years. Special relativity says that you can't pass another rocket through space at speeds faster than the speed of light, but nothing says that the space itself cannot expand faster than light. For those very distant bubbles, the bubble wall could never cross the ever-widening gap separating you from them. But if a bubble formed inside that 28-billion-light-year radius, its bubble wall would hit us and we would die as surely as that fly on the windshield. The risk of such destruction is very low. Statistically speaking, it's not likely to happen for another 10130 years, because the rate at which bubbles form is so exceedingly slow. There are more pressing threats to human existence. A vacuum-energy bubble could hit us before next year, but the chances of that are just 1/10130. Put another way, the bubbles are forming so far apart that they do not percolate to fill the space like the froth on the top of a beer. Rather, they are like bubbles in an eternally fizzing, infinitely expanding Champagne bath – if you can imagine such a thing. Things get especially interesting in the intermediate case: not inside or outside the bubble, but right on its surface. Now imagine you are a massive elementary particle sitting on the outside of the bubble just after it forms. For example, you might be one of the WIMPs (weakly interacting massive particles) we think make up most of the matter holding clusters of galaxies together. Such particles might have masses of order 1,000 times that of a proton. The bubble wall is accelerating outward, pushing you faster and faster. You would feel an acceleration of 1034 times the acceleration you feel sitting on the surface of the Earth. Astronauts can stand only about 10 Gs acceleration in their spaceships. But being an elementary particle, you are tough.

According to Einstein's equivalence principle, acceleration due to motion (as in a rocket ship firing its engines) and acceleration due to gravity (as on the surface of the Earth) are indistinguishable. You, the WIMP particle, could think you were sitting not on an accelerating glass-like vacuum bubble, but on a massive glass-ball planet with a radius of 10-16centimetres. As the bubble wall pushed you outward, closer and closer to the speed of light, your clock would tick slower and slower, lengths along the direction of motion would contract, and your ideas of simultaneity would change. (These are more effects of special relativity.) As you moved closer to the speed of light you'd feel as if the current time was still simultaneous with the time the bubble was created. Also, because of length contraction, you'd think you were no further from the centre of the bubble than when you started. Strange as it sounds, you would not experience the expanding bubble at all. You could think the bubble was static, and that you were sitting on a massive glass planet of fixed radius. You might be curious and try to run some experiments. If you sent a light beam outward, it would escape to infinity, because it would still outrun the expanding bubble wall. But if you sent a light beam horizontal to the surface of the glass planet, you'd see it skim along the surface as if it were orbiting; the expanding bubble would keep up with the beam as it moves outward. If you threw a ball upward from the surface at less than the velocity of light, you'd eventually catch up with it as the bubble wall continues accelerating outward. Sitting on the bubble surface, this would look to you like tossing up a ball on the surface of Earth and catching it as it fell back down under the planet's gravity. This scenario describes what would happen under the laws of physics as we understand them today. But Arkani-Hamed thinks that there might be additional effects in play at extremely high energies, far beyond anything that physicists can probe using the Large Hadron Collider, which discovered the Higgs particle. If so, we might be safe from a bubble disaster for much longer than even the previous calculation indicated. According to the cosmologist Andrei Linde at Stanford University, we might see bubbles forming inside our visible Universe only after 10 (raised to the power 1034) years. That's a 1 followed by 1034 zeros, a number far too large to write out. The additional high-energy physics effects would also change the conditions inside the bubbles, in a rather intriguing way. In this case, we expect the vacuum energy inside the bubbles to be less than the current vacuum energy density of 7 x 10-30 grammes per cubic centimetre, but it might be greater than zero. Such a bubble would still expand forever. The positive density inside the bubble would be less than outside, and the negative pressure inside would be less negative than the negative pressure outside, so the more negative pressure outside would still win and pull the bubble wall outward forever. The wall would again quickly accelerate to nearly the velocity of light. But inside the bubble, life would no longer be so miserable. The low positive vacuum energy could theoretically decay into particles. The inside of the bubble could become a self-contained bubble universe. As the bubble expands forever, the volume of this universe would increase without limit, and it could theoretically form an endless number of low-energy ‘galaxies’ or other objects inside. Suddenly, the bubble starts to sound less like exotic theoretical speculation, and more like the kind of physical reality that we know.

In 1981, the physicist Alan Guth at the Massachusetts Institute of Technology developed a theory of inflation which proposed that, when our Universe first formed, there was a brief period of very high vacuum energy and very high negative vacuum pressure. During that early stage, the Universe inflated very rapidly. The theory of inflation solved many major mysteries in cosmology, but came with some problems of its own. Sidney Coleman at Harvard University showed that such a vacuum state would decay by forming bubbles, much like the ones we have been discussing here. An inflating sea of low-density bubbles is highly non-uniform, whereas we can observe that the real Universe is smooth overall.

A year later, I propose a solution: perhaps our Universe is simply one of the expanding bubbles. From inside one of the bubbles the Universe would appear uniform, because we would be seeing only our own bubble and the uniform inflating sea that preceded it. Building on this idea, I proposed that our Universe was just one of myriad bubble universes forming and expanding in a high-density inflating sea. This universe of universes is now called a multiverse.Within a short time, independent papers appeared by Linde and by two other physicists, Andreas Albrecht, now of the University of California at Davis, and Paul Steinhardt of Princeton University. They proposed detailed particle physics scenarios that would allow such a bubble multiverse to emerge. Later that same year (1982), Stephen Hawking at Cambridge University wrote a paper on single-bubble inflation referencing all of our papers. He noted that a rapidly inflating bubble would produce random quantum fluctuations that would then be tremendously stretched into large-scale structures. Then in 1986 I showed that such structures would naturally lead to a sponge-like pattern of galaxy clusters connected by filaments of galaxies. That pattern has since been verified by numerous large-scale cosmic surveys; it is known as the cosmic web. The theory of inflation in the early Universe explains how the Universe began expanding some 13.8 billion years ago, in the first moments of the Big Bang, and describes, in beautiful detail, the small fluctuations we see in the microwave background radiation left over from the Big Bang. These spectacular successes of inflation lead us to believe that our Universe emerged from a very high-density vacuum state accompanied by a negative pressure of equal magnitude. It seems pretty clear that once you get inflation started, it is hard to stop it. Inflation should go on forever, creating a multiverse that will continue to spawn bubble universes eternally. Although we can't see these other bubble universes, we have theoretical reasons to believe that they exist, because inflation seems to imply that our Universe is not a one-time event. But perhaps the best evidence for inflation in the early Universe is the fact that we see a low-grade version of inflation starting in the Universe now: the current accelerated expansion of the Universe.

Here our story comes full circle. Kirshner's investigation of distant supernovae eventually led to the discovery that the cosmos appears to be accelerating under the influence of vacuum energy. Theoretical explorations of vacuum energy indicated it could create bubble universes. And the modern formulation of inflationary cosmology ties both of these ideas together. When inflation was first proposed, no one knew whether a positive energy/negative pressure vacuum state could even exist. Now we know that it can. We know, because we are living in it! Maybe we are seeing today, in the accelerating fleeing of distant galaxies all around us, a low-density recapitulation of the physics that produced our own Universe billions of years ago. And maybe we don't have to speculate about what life is like inside a bubble. It might be the only reality we know.

Adapted from Aeon

<u>Exercise III</u>.

Fill in the gaps.

1) How is it that we can observe the _______________ once again, hundreds of years later?

2) An alternative production method is the mechanical _______________ of cold neutrons.

3) Its temperature, ____________, age, and location do not match up with any theory.

4) Further examination was needed to ______________ the full extent of damage, they said.

5) The larger the star, the greater it's ________________ might be on nearby comets.

6) The significance of this decision has yet to ______________ the public consciousness.

7) The Dutch physicist Hendrik Casimir first noted this ______________ movement in 1948.

8) Things need to ______________ a bit before they are ready to be examined more closely.

9) The cluster pair is connected by a _____________ permeated by hot X-ray emitting gas.

10) The transition from the development to the _______________ is a crucial moment in the work.

Exercise IV.

Make up sentences of your own with the following word combinations: repulsive gravitational effect, to skim along, to toss up, to get an answer, in essence, the farther out we look, the farther back in time we see, look out at, slowing down, speeding up

Exercise V.

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

to ascertain	extremely small; tiny
unaccounted	find (something) out for certain; make sure of
bizarre	a window at the front of the passenger compartment of a motor vehicle
magnitude	very strange or unusual, esp. so as to cause interest or amusement
to flee	not included in (an account or calculation) through being lost or disregarded
windshield	size

minuscule	run away from a place or situation of danger
fizzing	filter gradually through a porous surface or substance
growth	produce bubbles of gas and make a hissing sound
to percolate	the process of increasing in physical size

Exercise VI.

Identify the part of speech the words belong to.

deceleration, luminosity, filament, recapitulation, cosmic, reality, direction, modern, cosmology, visible,

Exercise VII.

Match the words to make word combinations:

intrinsic	pull
energy	scale
standard	density
gravitational	numbers
graduate	Bang
modern	reality
distance	luminosity
accurate	lampposts
Big	cosmology

cosmic	student

Exercise VIII.

Summarize the article “ Universe in a bubble”

4. Radical dimensions

Exercise I.

Say what Russian words help to guess the meaning of the following words: radical, theory, reality, architecture, structure, innovation, culture, transition, transformation, geometrical

Exercise II.

Make sure you know the following words and word combinations.
otherthrow, spatialised, void, grid, steep, allied, trampoline, to balk, infinitesimal, googol

Radical dimensions

Relativity says we live in four dimensions. String theory says it’s 10. What are ‘dimensions’ and how do they affect reality?

Our architecture, our education and our dictionaries tell us that space is three-dimensional. Yet the notion that we inhabit a space with any mathematical structure is a radical innovation of Western culture, necessitating an overthrow of long-held beliefs about the nature of reality. Although the birth of modern science is often discussed as a transition to a mechanistic account of nature, arguably more important – and certainly more enduring – is the transformation it entrained in our conception of space as a geometrical construct. Over the past century, the quest to describe the geometry of space has become a major project in theoretical physics, with experts from Albert Einstein onwards attempting to explain all the fundamental forces of nature as byproducts of the shape of space itself. While on the local level we are trained to think of space as having three dimensions, general relativity paints a picture of a four-dimensional universe, and string theory says it has 10 dimensions – or 11 if you take an extended version known as M-Theory. There are variations of the theory in 26 dimensions, and recently pure mathematicians have been electrified by a version describing spaces of 24 dimensions. But what are these 'dimensions'? And what does it mean to talk about a 10-dimensional space of being? In order to come to the modern mathematical mode of thinking about space, one first has to conceive of it as some kind of arena that matter might occupy. At the very least, 'space' has to be thought of as something extended. Obvious though this might seem to us, such an idea was anathema to Aristotle, whose concepts about the physical world dominated Western thinking in late antiquity and the Middle Ages. Strictly speaking, Aristotelian physics didn't include a theory of space, only a concept of place. Think of a cup sitting on a table. For Aristotle, the cup is surrounded by air, itself a substance. In his world picture, there is no such thing as empty space, there are only boundaries between one kind of substance, the cup, and another, the air. Or the table. For Aristotle, 'space' (if you want to call it that), was merely the thin boundary between the cup and what surrounds it. Without extension, space wasn't something anything else could be in. Centuries before Aristotle, there was a theory of reality that invoked an inherently spatialised way of seeing – an ‘atomistic’ vision, whereby the material world is composed of minuscule particles (or atoms) moving through a void. But Aristotle rejected atomism, claiming that the very concept of a void was logically incoherent. By definition, he said, ‘nothing’ cannot be. Overcoming Aristotle’s objection to the void, and thus to the concept of extended space, would be a project of centuries. Not until Galileo and Descartes made extended space one of the cornerstones of modern physics in the early 17th century does this innovative vision come into its own. For both thinkers, as the American philosopher Edwin Burtt put it in 1924, ‘physical space was assumed to be identical with the realm of geometry’ – that is, the three-dimensional Euclidean geometry we are now taught in school. Long before physicists embraced the Euclidean vision, painters had been pioneering a geometrical conception of space, and it is to them that we owe this remarkable leap in our conceptual framework. During the late Middle Ages a view began to percolate in Europe that God had created the world according to the laws of Euclidean geometry. Hence, if artists wished to portray it truly, they should emulate the Creator in their representational strategies. From the 14th to the 16th centuries, artists developed the techniques of what came to be known as perspective. By consciously exploring geometric principles, these painters gradually learned how to construct images of objects in three-dimensional space. In the process, they reprogrammed European minds to see space in a Euclidean fashion. In a very literal fashion, perspectival representation was a form of virtual reality that, like today’s VR games, aimed to give viewers the illusion that they had been transported into geometrically coherent and psychologically convincing other worlds.

By the end of the 17th century, Isaac Newton had expanded this Galilean vision to encompass the universe at large, which now became a potentially infinite three-dimensional vacuum – a vast, quality-less, emptiness extending forever in all directions. The structure of the 'real' had thus been transformed from a philosophical and theological question into a geometrical proposition. Where painters had used mathematical tools to develop new ways of making images, now, at the dawn of the 'scientific revolution', Descartes discovered a way to make images of mathematical relations in and of themselves. In the process, he formalised the concept of a dimension, and injected into our consciousness not only a new way of seeing the world but a new tool for doing science. Almost everyone today recognises the fruits of Descartes's genius in the image of the Cartesian plane – a rectangular grid marked with an x and y axis, and a coordinate system. By definition, the Cartesian plane is a two-dimensional space because we need *two* coordinates to identify any point within it. Descartes discovered that with this framework he could link geometric shapes and equations. Thus, a circle with a radius of 1 can be described by the equation $x2 + y2 =1$. A vast array of figures that we can draw on this plane can be described by equations, and such 'analytic' or 'Cartesian' geometry would soon become the basis for the calculus developed by Newton and G W Leibniz to further physicists' analysis of motion. One way to understand calculus is as the study of curves; so, for instance, it enables us to formally define where a curve reaches a local maximum or minimum. When applied to the study of motion, calculus gives us a way to analyse and predict where, for instance, an object thrown into the air will reach a maximum height, or when a ball rolling down a curved slope will reach a specific speed. Since its invention, calculus has become a vital tool for almost every branch of science. Thus with an x, y and z axis, we can describe the surface of a sphere – as in the skin of a ball. Here the equation (for a sphere with a radius of 1) becomes: $x2 + y2 + z2 = 1$ With three axes, we can describe forms in three-dimensional space. And again, every point is uniquely identified by three coordinates: it's the necessary condition of three-ness that makes the space three-dimensional. But why stop there? What if I add a fourth dimension? Let's call it 'p'. Now I can write an equation for something I claim is a sphere sitting in four-dimensional space: $x2 + y2 + z2 + p2 = 1$. I can't draw this object for you, yet mathematically the addition of another dimension is a legitimate move. 'Legitimate' meaning there's nothing logically inconsistent about doing so – there's no reason I can't. And I can keep on going, adding more dimensions. So I define a sphere in five-dimensional space with five coordinate axes and so on. Although I might not be able to visualise higher-dimensional spheres, I can describe them symbolically.

Mathematically, I can describe a sphere in any number of dimensions I choose. All I have to do is keep adding new coordinate axes, what mathematicians call 'degrees of freedom'. From the perspective of mathematics, a 'dimension' is nothing more than another coordinate axis (another degree of freedom), which ultimately becomes a purely symbolic concept not necessarily linked at all to the material world. In the 1860s, the pioneering logician Augustus De Morgan summed up the increasingly abstract view of this field by noting that mathematics is purely 'the science of symbols', and as such doesn't have to relate to anything other than itself. Unlike mathematicians, who are at liberty to play in the field of ideas, physics is bound to nature, and at least in principle, is allied with material things. Yet all this raises a liberating possibility, for if mathematics allows for more than three dimensions, and we think mathematics is useful for describing the world, how do we know that physical space is limited to three? Although Galileo and Newton had taken length, breadth and height to be axiomatic, might there not be more dimensions to our world? In the late 19th and early 20th centuries, a raft of authors and artists explored ideas about the fourth dimension and what it might mean for humans to encounter it. Then in 1905, an unknown physicist named Albert Einstein published a paper describing the real world as a four-dimensional setting. In his 'special theory of relativity', time was added to the three classical dimensions of space. In the mathematical formalism of relativity, all four dimensions are bound together, and the term spacetime entered our lexicon. This assemblage was by no means arbitrary. Einstein found that, by going down this path, a powerful mathematical apparatus came into being that transcended Newton's physics and enabled him to predict the behaviour of electrically charged particles. Only in a 4D model of the world can electromagnetism be fully and accurately described. Relativity was a great deal more than another literary game, especially once Einstein extended it from the 'special' to the 'general' theory. Now multidimensional space became imbued with deep physical meaning. In Newton's world picture, matter moves through space in time under the influence of natural forces, particularly gravity. Space, time, matter and force are distinct categories of reality. With special relativity, Einstein demonstrated that space and time were unified, thus reducing the fundamental physical categories from four to three: spacetime, matter and force. General relativity takes a further step by enfolding the force of gravity into the structure of spacetime itself.

To comprehend this remarkable situation, let's imagine for the moment its two-dimensional analogue. Think of a trampoline, and imagine we draw on its surface a Cartesian grid. Now put a bowling ball onto the grid. Around it, the surface will stretch and warp so some points become further away from each other. We've disturbed the inherent measure of distance within the space, making it uneven. General relativity says that this warping is what a heavy object, such as the Sun, does to spacetime, and the aberration from Cartesian perfection of the space itself gives rise to the phenomenon we experience as gravity. Whereas in Newton's physics, gravity comes out of nowhere, in Einstein's it arises naturally from the inherent geometry of a four-dimensional manifold; in places where the manifold stretches most, or deviates most from Cartesian regularity, gravity feels stronger. This is sometimes referred to as 'rubber-sheet physics'. Here, the vast cosmic force holding planets in orbit around stars, and stars in orbit around galaxies, is nothing more than a side-effect of warped space. Gravity is literally geometry in action. If moving into four dimensions helps to explain gravity, then might thinking in five dimensions have any scientific advantage? Why not give it a go? a young Polish mathematician named Theodor Kaluza asked in 1919, thinking that if Einstein had absorbed gravity into spacetime, then perhaps a further dimension might similarly account for the force of electromagnetism as an artifact of spacetime's geometry. So Kaluza added another dimension to Einstein's equations, and to his delight found that in five dimensions both forces fell out nicely as artifacts of the geometric model. The mathematics fit like magic, but the problem in this case was that the additional dimension didn't seem to correlate with any particular physical quality. In general relativity, the fourth dimension was time; in Kaluza's theory, it wasn't anything you could point to, see, or feel: it was just there in the mathematics. Even Einstein balked at such an ethereal innovation. What is it? he asked. Where is it? In 1926, the Swedish physicist Oskar Klein answered this question in a way that reads like something straight out of Wonderland. Imagine, he said, you are an ant living on a long, very thin length of hose. You could run along the hose backward and forward without ever being aware of the tiny circle-dimension under your feet. Only your ant-physicists with their powerful ant-microscopes can see this tiny dimension. According to Klein, every point in our four-dimensional spacetime has a little extra circle of space like this that's too tiny for us to see. Since it is many orders of magnitude smaller than an atom, it's no wonder we've missed it so far. Only physicists with super-powerful particle accelerators can hope to see down to such a minuscule scale. Once physicists got over their initial shock, they became enchanted by Klein's idea, and during the 1940s the theory was elaborated in great mathematical detail and set into a quantum context. Unfortunately, the infinitesimal scale of the new dimension made it impossible to imagine how it could be experimentally verified. Klein calculated that the diameter of the tiny circle was just 10-30 cm. By comparison, the diameter of a hydrogen atom is 10-8 cm, so we're talking about something more than 20 orders of magnitude smaller than the smallest atom. Even today, we're nowhere close to being able to see such a minute scale. And so the idea faded out of fashion.

By the 1960s, physicists had discovered two additional forces of nature, both operating at the subatomic scale. Called the weak nuclear force and the strong nuclear force, they are responsible for some types of radioactivity and for holding quarks together to form the protons and neutrons that make up atomic nuclei. In the late 1960s, as physicists began to explore the new subject of string theory (which posits that particles are like minuscule rubber bands vibrating in space), Kaluza's and Klein's ideas bubbled back into awareness, and theorists gradually began to wonder if the two subatomic forces could also be described in terms of spacetime geometry. It turns out that in order to encompass both of these two forces, we have to add another five dimensions to our mathematical description. There's no reason it should be five; and, again, none of these additional dimensions relates directly to our sensory experience. They are just there in the mathematics. So this gets us to the 10 dimensions of string theory. Here there are the four large-scale dimensions of spacetime (described by general relativity), plus an extra six 'compact' dimensions (one for electromagnetism and five for the nuclear forces), all curled up in some complex, scrunched-up, geometric structure. A great deal of effort is being expended by physicists and mathematicians to understand all the possible shapes that this miniature space might take, and which, if any, of the many alternatives is realised in the real world. Technically, these forms are known as Calabi-Yau manifolds, and they can exist in any even number of higher dimensions. A 2D slice through them (about the best we can do in visualising what they look like) brings to mind the crystalline structures of viruses; they almost look alive. There are many versions of string-theory equations describing 10-dimensional space, but in the 1990s the mathematician Edward Witten showed that things could be somewhat simplified if we took an 11-dimensional perspective. He called his new theory M-Theory, and enigmatically declined to say what the 'M' stood for. Usually it is said to be 'membrane', but 'matrix', 'master', 'mystery' and 'monster' have also been proposed. So far, we have no evidence for any of these additional dimensions, but string theory has turned out to have powerful implications for mathematics itself. Recently, developments in a version of the theory that has 24 dimensions has shown unexpected interconnections between several major branches of mathematics, which means that, even if string theory doesn't pan out in physics, it will have proven a richly rewarding source of purely theoretical insight. In mathematics, 24-dimensional space is rather special – magical things happen there, such as the ability to pack spheres together in a particularly elegant way – though it's unlikely that the real world has 24 dimensions. For the world we love and live in, most string theorists believe that 10 or 11 dimensions will prove sufficient.

There is one final development in string theory that warrants attention. In 1999, Lisa Randall and Raman Sundrum proposed that there might be an additional dimension on the cosmological scale, the scale described by general relativity. According to their 'brane' theory – 'brane' being short for 'membrane' – what we normally call our Universe might be embedded in a vastly bigger five-dimensional space, a kind of super-universe. Within this super-space, ours might be just one of a whole array of co-existing universes, each a separate 4D bubble within a wider arena of 5D space. It is hard to know if we'll ever be able to confirm Randall and Sundrum's theory. However analogies have been drawn between this idea and the dawn of modern astronomy. Europeans 500 years ago found it impossible to imagine other physical 'worlds' beyond our own, yet now we know that the Universe is populated by billions of other planets orbiting around billions of other stars. Who knows, one day our descendants could find evidence for billions of other universes, each with their own unique spacetime equations. The project of understanding the geometrical structure of space is one of the signature achievements of science, but it might be that physicists have reached the end of this road. For it turns out that, in a sense, Aristotle was right – there are indeed logical problems with the notion of extended space. For all the extraordinary successes of relativity, we know that its description of space cannot be the final one because at the quantum level it breaks down. For the past half-century, physicists have been trying without success to unite their understanding of space at the cosmological scale with what they observe at the quantum scale, and increasingly it seems that such a synthesis could require radical new physics. A view is emerging among some theoretical physicists that space might in fact be an emergent phenomenon created by something more fundamental, in much the same way that temperature emerges as a macroscopic property resulting from the motion of molecules. A leading proponent of new ways of thinking about space is the cosmologist Sean Carroll at Caltech, who recently said that classical space isn't 'a fundamental part of reality's architecture', and argued that we are wrong to assign such special status to its four or 10 or 11 dimensions. Carroll invites us to consider 'wetness', an emergent phenomenon of lots of water molecules coming together. No individual water molecule is wet, only when you get a bunch of them together does wetness come into being as a quality. So, he says, space emerges from more basic things at the quantum level. Carroll writes that, from a quantum perspective, the Universe 'evolves in a mathematical realm with more than 10(10^100) dimensions' – that's 10 followed by a googol of zeroes, or 10,000 trillion trillion trillion trillion trillion trillion trillion trillion zeroes. Even Descartes might have been stunned by where his vision has taken us, and what dazzling complexity has come to be contained in the simple word 'dimension'.

Adapted from Aeon

Exercise III.

Fill in the gaps.

1) That would ______________ faster spaceships or manipulation of the time continuum.

2) Effectively managing conflict is ___________ the hardest thing a manager has to do.

3) Maxwell's equations provide for an electric charge, but _____________ no magnetic charge.

4) All these technologies need nozzles to squirt out ___________ droplets of liquid.

5) Chemically inert, it can ____________ out of the ground into basements.

6) But one model he doesn't want to ____________ is the British constitutional monarchy.

7) Special cases with less _________________ are the circular and parabolic orbit.

8) Each region is distinct from the others providing a unique habitat ____________.

9) Other ways in which singularities occur is by degeneration of ____________ structure.

10) Despite such ____________ thickness, it consists of several layers of particles.

Exercise IV.

Make up sentences of your own with the following word combinations: degrees of freedom, to fall out, scrunched up, to pan out, to endure, to posit, to percolate, to emulate, to enfold, to enchant

Exercise V.

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

assemblage	an object made by a human being, typically an item of cultural or historical interest
to expend	many and various
arena	surround and have or hold within
anathema	a work of art made by grouping found or unrelated objects
coherent	spend or use up (a resource such as money, time,

	or energy)
artifact	a level area surrounded by seats for spectators, in which sports, entertainments, and other public events are held
arbitrary	something or someone that one vehemently dislikes
to encompass	logical and consistent
manifold	based on random choice or personal whim, rather than any reason or system

<u>Exercise VI.</u>

Identify the part of speech the words belong to: arguably, aberration, ethereal, dimensions, education, notion, mathematical, radical, innovation, transition

<u>Exercise VII.</u>

Match the words to make word combinations:

Cartesian	attempting
rubber-sheet	structure
geometrical	beliefs
four-dimensional	dimensions
general	universe

fundamental	plane
long-held	relativity
onwards	physics
radical	forces
mathematical	construct

<u>Exercise VIII</u> .

Summarize the article “Radical dimensions”

SUPPLEMENTARY READING

But is it science?

Theoretical physicists who say the multiverse exists set a dangerous precedent: science based on zero empirical evidence

There is no agreed criterion to distinguish science from pseudoscience, or just plain ordinary bullshit, opening the door to all manner of metaphysics masquerading as science. This is 'post-empirical' science, where truth no longer matters, and it is potentially very dangerous.

It's not difficult to find recent examples. On 8 June 2019, the front cover ofNew Scientist magazine boldly declared that we're 'Inside the Mirrorverse'. Its editors bid us 'Welcome to the parallel reality that's hiding in plain sight'.

How you react to such headlines likely depends on your familiarity not only with aspects of modern physics, but also with the sensationalist tendencies of much of the popular-science media. Needless to say, the feature in question is rather less sensational than its headline suggests. It's about the puzzling difference in the average time that subatomic particles called neutrons will freely undergo radioactive decay, depending on the experimental technique used to measure this – a story unlikely to pique the interests of more than a handful of New Scientist's readers.

But, as so often happens these days, a few physicists have suggested that this is a problem with 'a very natural explanation'. They claim that the neutrons are actually flitting between parallel universes. They admit that the chances of proving this are 'low', or even 'zero', but it doesn't really matter. When it comes to grabbing attention, inviting that all-important click, or purchase, speculative metaphysics wins hands down.

It would be easy to lay the blame for this at the feet of science journalists or popular-science writers. But it seems that the scientists themselves (and their PR departments) are equally culpable. The New Scientist feature is concerned with the work of Leah Broussard at the US Department of Energy's Oak Ridge National Laboratory. As far as I can tell, Broussard is engaged in some perfectly respectable experimental research on the properties of neutrons. But she betrays the nature of the game that's being played when she says: 'Theorists are very good at evading the traps that experimentalists leave for them. You'll always find someone who's happy to keep the idea alive.'

The 'mirrorverse' is just one more in a long line of so-called multiverse theories. These theories are based on the notion that our Universe is not unique, that there exists a large number of other universes that somehow sit alongside or parallel to our own. For example, in the so-called Many-Worlds interpretation of quantum mechanics, there are universes containing our parallel selves, identical to us but for their different experiences of quantum physics. These theories are attractive to some few theoretical physicists and philosophers, but there is absolutely no empirical evidence for them. And, as it seems we can't ever experience these other universes, there will never be any evidence for them. As Broussard explained, these theories are sufficiently slippery to duck any kind of challenge that experimentalists might try to throw at them, and there's always someone happy to keep the idea alive.

Is this really science? The answer depends on what you think society needs from science. In our post-truth age of casual lies, fake news and alternative facts, society is under extraordinary pressure from those pushing potentially dangerous antiscientific propaganda – ranging from climate-change denial to the anti-vaxxer movement to homeopathic medicines. I, for one, prefer a science that is rational and based on evidence, a science that is concerned with theories and empirical facts, a science that promotes the search for truth, no matter how transient or contingent. I prefer a science that does not readily admit theories so vague and slippery that empirical tests are either impossible or they mean absolutely nothing at all.

But isn't science in any case about what is right and true? Surely nobody wants to be wrong and false? Except that it isn't, and we seriously limit our ability to lift the veils of ignorance and change antiscientific beliefs if we persist in peddling this absurdly simplistic view of what science is. To understand why post-empirical science is even possible, we need first to dispel some of science's greatest myths.

Despite appearances, science offers no certainty. Decades of progress in the philosophy of science have led us to accept that our prevailing scientific understanding is a limited-time offer, valid only until a new observation or experiment proves that it's not. It turns out to be impossible even to formulate a scientific theory without metaphysics, without first assuming some things we can't actually prove, such as the existence of an objective reality and the invisible entities we believe to exist in it. This is a bit awkward because it's difficult, if not impossible, to gather empirical facts without first having some theoretical understanding of what we think we're doing. Just try to make any sense of the raw data produced by CERN's Large Hadron Collider without recourse to theories of particle physics, and see how far you get. Theories are underdetermined: choosing between competing theories that are equivalently accommodating of the facts can become a matter for personal judgment, or our choice of metaphysical preconceptions or prejudices, or even just the order in which things happened historically. This is one of the reasons why arguments still rage about the interpretation of a quantum theory that was formulated nearly 100 years ago.

Yet history tells us quite unequivocally that science works. It progresses. We know (and we think we understand) more about the nature of the physical world than we did yesterday; we know more than we did a decade, or a century, or a millennium ago. The progress of science is the reason we have smartphones, when the philosophers of Ancient Greece did not.

Successful theories are essential to this progress. When you use Google Maps on your smartphone, you draw on a network of satellites orbiting Earth at 20,000 kilometres, of which four are needed for the system to work, and between six and 10 are 'visible' from your location at any time. Each of these satellites carries a miniaturised atomic clock, and transmits precise timing and position data to your device that allow you to pinpoint your location and identify the fastest route to the pub. But without corrections based on Albert Einstein's special and general theories of relativity, the Global Positioning System would accumulate clock errors, leading to position errors of up to 11 kilometres per day. Without these rather abstract and esoteric – but nevertheless highly successful – theories of physics, after a couple of days you'd have a hard time working out where on Earth you are.

In February 2019, the pioneers of GPS were awarded the Queen Elizabeth Prize for Engineering. The judges remarked that 'the public may not know what [GPS] stands for, but they know what it is'. This suggests a rather handy metaphor for science. We might scratch our heads about how it works, but we know that, when it's done properly, it does.

And this brings us to one of the most challenging problems emerging from the philosophy of science: its strict definition. When is something 'scientific', and when is it not? In the light of the metaphor above, how do we know when science is being 'done properly'? This is the demarcation problem, and it has an illustrious history. (For a more recent discussion, see Massimo Pigliucci's essay 'Must Science Be Testable?' on Aeon).

The philosopher Karl Popper argued that what distinguishes a scientific theory from pseudoscience and pure metaphysics is the possibility that it might be falsified on exposure to empirical data. In other words, a theory is scientific if it has the potential to be proved wrong.

Astrology makes predictions, but these are intentionally general and wide open to interpretation. In 1963, Popper wrote: 'It is a typical soothsayer's trick to predict things so vaguely that the predictions can hardly fail: that they become irrefutable.' We can find many ways to criticise the premises of homeopathy and dismiss this as pseudoscience, as it has little or no foundation in our current understanding of Western, evidence-based medicine. But, even if we take it at face value, we should admit that it fails all the tests: there is no evidence from clinical trials for the effectiveness of homeopathic remedies beyond a placebo effect. Those who, like Prince Charles, continue to argue for its efficacy are not doing science. They are doing wishful-thinking or, like a snake-oil salesman, they're engaged in deliberate deception.

And, no matter how much we might want to believe that God designed all life on Earth, we must accept that intelligent design makes no testable predictions of its own. It is simply a conceptual alternative to evolution as the cause of life's incredible complexity. Intelligent design cannot be falsified, just as nobody can prove the existence or non-existence of a philosopher's metaphysical God, or a God of religion that 'moves in mysterious ways'. Intelligent design is not science: as a theory, it is simply overwhelmed by its metaphysical content.

But it was never going to be as simple as this. Applying a theory typically requires that – on paper, at least – we simplify the problem by imagining that the system we're interested in can be isolated, such that we can ignore interference from the rest of the Universe. In his book Time Reborn (2013), the theoretical physicist Lee Smolin calls this 'doing physics in a box', and it involves making one or more so-called auxiliary assumptions. Consequently, when predictions are falsified by the empirical evidence, it's never clear why. It might be that the theory is false, but it could simply be that one of the auxiliary assumptions is invalid. The evidence can't tell us which.

There's a nice lesson on all this from planetary astronomy. In 1781, Isaac Newton's laws of motion and gravitation were used to predict the orbit of a newly discovered planet called Uranus. The prediction was wrong. But instead of accepting that Newton's laws were thus falsified, the problem was solved simply by tinkering with the auxiliary assumptions, in this case by making the box a little bigger. John Adams and Urbain Le Verrier independently proposed that there was an as-yet-unobserved eighth planet in the solar system that was perturbing the orbit of Uranus. Neptune was duly discovered, in 1846, very close to the position predicted by Le Verrier. Far from falsifying Newton's laws, the incorrect prediction and subsequent discovery of Neptune was greeted as a triumphant confirmation of them.

A few years later, Le Verrier tried the same logic on another astronomical problem. The planetary orbits are not exact ellipses. With each orbit, each planet's point of closest approach to the Sun (called the perihelion) shifts slightly, or precesses, and this was thought to be caused by the cumulative gravitational pull of all the other planets in the solar system. For the planet Mercury, lying closest to the Sun, Newton's laws predict a precession of 532 arc-seconds per century. But today the observed precession is rather more, about 575 arc-seconds per century, a difference of 43 arc-seconds. Though small, this difference accumulates and is equivalent to one 'extra' orbit every 3 million years or so.

Le Verrier ascribed this difference to the effects of yet another unobserved planet, lying closer to the Sun than Mercury, which became known as Vulcan. Astronomers searched for it in vain. In this case, Newton's laws were indeed playing false. Einstein was delighted to discover that his general theory of relativity predicts a further 'relativistic' contribution of 43 arc-seconds per century, due to the curvature of spacetime around the Sun in the vicinity of Mercury.

This brief tale suggests that scientists will stop tinkering and agree to relegate a theory only when a demonstrably better one is available to replace it. We could conclude from this that theories are never falsified, as such. We know that Newton's laws of motion are inferior to quantum mechanics in the microscopic realm of molecules, atoms and sub-atomic particles, and they break down when stuff of any size moves at or close to the speed of light. We know that Newton's law of gravitation is inferior to Einstein's general theory of relativity. And yet Newton's laws remain perfectly satisfactory when applied to 'everyday' objects and situations, and physicists and engineers will happily make use of them. Curiously, although we know they're 'not true', under certain practical circumstances they're not false either. They're 'good enough'.

Such problems were judged by philosophers of science to be insurmountable, and Popper's falsifiability criterion was abandoned (though, curiously, it still lives on in the minds of many practising scientists). But rather than seek an alternative, in

1983 the philosopher Larry Laudan declared that the demarcation problem is actually intractable, and must therefore be a pseudo-problem. He argued that the real distinction is between knowledge that is reliable or unreliable, irrespective of its provenance, and claimed that terms such as ‘pseudoscience’ and ‘unscientific’ have no real meaning.

But, for me at least, there has to be a difference between science and pseudoscience; between science and pure metaphysics, or just plain ordinary bullshit. So, if we can’t make use of falsifiability, what do we use instead? I don’t think we have any real alternative but to adopt what I might call the empirical criterion. Demarcation is not some kind of binary yes-or-no, right-or-wrong, black-or-white judgment. We have to admit shades of grey. Popper himself was ready to accept this:
the criterion of demarcation cannot be an absolutely sharp one but will itself have degrees. There will be well-testable theories, hardly testable theories, and non-testable theories. Those which are non-testable are of no interest to empirical scientists. They may be described as metaphysical.

Here, ‘testability’ implies only that a theory either makes contact, or holds some promise of making contact, with empirical evidence. It makes no presumptions about what we might do in light of the evidence. If the evidence verifies the theory, that’s great – we celebrate and start looking for another test. If the evidence fails to support the theory, then we might ponder for a while or tinker with the auxiliary assumptions. Either way, there’s a tension between the metaphysical content of the theory and the empirical data – a tension between the ideas and the facts – which prevents the metaphysics from getting completely out of hand. In this way, the metaphysics is tamed or ‘naturalised’, and we have something to work with. This is science.

Now, this might seem straightforward, but we’ve reached a rather interesting period in the history of foundational physics. Today, we’re blessed with two extraordinary theories. The first is quantum mechanics. This is the basis for the so-called standard model of particle physics that describes the workings of all known elementary particles. It is our best theory of matter. The second is Einstein’s general theory of relativity that explains how gravity works, and is the basis for the so-called standard model of Big Bang cosmology. It is our best theory of space, time and the Universe.

These two standard models explain everything we can see in the Universe. Yet they are deeply unsatisfying. The charismatic physicist Richard Feynman might have been a poor philosopher, but he wasn’t joking when he wrote in 1965: ‘I think I can safely say that nobody understands quantum mechanics.’ To work satisfactorily, Big Bang cosmology requires rather a lot of ‘dark matter’ and ‘dark energy’, such that ‘what we can see’ accounts for an embarrassingly small 5 per cent of everything we believe there is in the Universe. If dark matter is really matter of some kind, then it’s simply missing from our best theory of matter. Changing one or more of the constants that govern the physics of our Universe by even the smallest amount would render the Universe inhospitable to life, or even physically impossible. We have no explanation for why the laws and constants of physics appear so 'fine-tuned' to evolve a Goldilocks universe that is just right.

These are very, very stubborn problems, and our best theories are full of explanatory holes. Bringing them together in a putative theory of everything has proved to be astonishingly difficult. Despite much effort over the past 50 years, there is no real consensus on how this might be done. And, to make matters considerably worse, we've run out of evidence. The theorists have been cunning and inventive. They have plenty of metaphysical ideas but there are no empirical signposts telling them which path they should take. They are ideas-rich, but data-poor.
They're faced with a choice.

Do they pull up short, draw back and acknowledge that, without even the promise of empirical data to test their ideas, there is little or nothing more that can be done in the name of science? Do they throw their arms in the air in exasperation and accept that there might be things that science just can't explain right now?

Or do they plough on regardless, publishing paper after paper filled with abstract mathematics that they can interpret to be explanatory of the physics, in the absence of data, for example in terms of a multiverse? Do they not only embrace the metaphysics but also allow their theories to be completely overwhelmed by it? Do they pretend that they can think their way to real physics, ignoring Einstein's caution:
Time and again the passion for understanding has led to the illusion that man is able to comprehend the objective world rationally by pure thought without any empirical foundations – in short, by metaphysics.

I think you know the answer. But to argue that this is nevertheless still science requires some considerable mental gymnastics. Some just double-down. The theoretical physicist David Deutsch has declared that the multiverse is as real as the dinosaurs once were, and we should just 'get over it'. Martin Rees, Britain's Astronomer Royal, declares that the multiverse is not metaphysics but exciting science, which 'may be true', and on which he'd bet his dog's life. Others seek to shift or undermine any notion of a demarcation criterion by wresting control of the narrative. One way to do this is to call out all the problems with Popper's falsifiability that were acknowledged already many years ago by philosophers of science. Doing this allows them to make their own rules, while steering well clear of the real issue – the complete absence of even the promise of any tension between ideas and facts.

Sean Carroll, a vocal advocate for the Many-Worlds interpretation, prefers abduction, or what he calls 'inference to the best explanation', which leaves us with theories that are merely 'parsimonious', a matter of judgment, and 'still might reasonably be true'. But whose judgment? In the absence of facts, what constitutes 'the best explanation'?

Carroll seeks to dress his notion of inference in the cloth of respectability provided by something called Bayesian probability theory, happily overlooking its entirely subjective nature. It's a short step from here to the theorist-turned-philosopher Richard Dawid's efforts to justify the string theory programme in terms of ‘theoretically confirmed theory’ and ‘non-empirical theory assessment’. The ‘best explanation’ is then based on a choice between purely metaphysical constructs, without reference to empirical evidence, based on the application of a probability theory that can be readily engineered to suit personal prejudices. Welcome to the oxymoron that is post-empirical science.

Still, what’s the big deal? So what if a handful of theoretical physicists want to indulge their inner metaphysician and publish papers that few outside their small academic circle will ever read? But look back to the beginning of this essay. Whether they intend it or not (and trust me, they intend it), this stuff has a habit of leaking into the public domain, dripping like acid into the very foundations of science. The publication of Carroll’sbook Something Deeply Hidden, about the Many-Worlds interpretation, has been accompanied by an astonishing publicity blitz, including an essay on Aeon last month. A recent PBS News Hour piece led with the observation that: ‘The “Many-Worlds” theory in quantum mechanics suggests that, with every decision you make, a new universe springs into existence containing what amounts to a new version of you.’

Physics is supposed to be the hardest of the ‘hard sciences’. It sets standards by which we tend to judge all scientific endeavour. And people are watching.

The historian of science Helge Kragh has spent some considerable time studying the ‘higher speculations’ that have plagued foundational physics throughout its history. But intelligent design is hardly less testable than many multiverse theories. To dismiss intelligent design on the ground that it is untestable, and yet to accept the multiverse as an interesting scientific hypothesis, may come suspiciously close to applying double standards. As seen from the perspective of some creationists, and also by some non-creationists, their cause has received unintended methodological support from multiverse physics.

Unsurprisingly, the folks at the Discovery Institute, the Seattle-based think-tank for creationism and intelligent design, have been following the unfolding developments in theoretical physics with great interest. The Catholic evangelist Denyse O’Leary, writing for the Institute’s Evolution News blog in 2017, suggests that: ‘Advocates [of the multiverse] do not merely propose that we accept faulty evidence. They want us to abandon evidence as a key criterion for acceptance of their theory.’ The creationists are saying, with some justification: look, you accuse us of pseudoscience, but how is what you’re doing in the name of science any different? They seek to undermine the authority of science as the last word on the rational search for truth.

The philosophers Don Ross, James Ladyman and David Spurrett haveargued that a demarcation criterion is a matter for institutions, not individuals. The institutions of science impose norms and standards and provide sense-checks and error filters that should in principle exclude claims to objective scientific knowledge derived from pure metaphysics. But, despite efforts by the cosmologist George Ellis and the astrophysicist Joe Silk to raise a red flag in 2014 and call on some of these institutions to ‘defend the integrity of physics’, nothing has changed. Ladyman seems resigned: ‘Widespread error about fundamentals among experts can and does happen,’ he tells me. He believes a correction will come in the long run, when a real scientific breakthrough is made. But what damage might be done while we wait for a breakthrough that might never come?

Perhaps we should begin with a small first step. Let’s acknowledge that theoretical physicists are perfectly entitled to believe, write and say whatever they want, within reason. But is it asking too much that they make their assertions with some honesty? Instead of ‘the multiverse exists’ and ‘it might be true’, is it really so difficult to say something like ‘the multiverse has some philosophical attractions, but it is highly speculative and controversial, and there is no evidence for it’? I appreciate that such caveats get lost or become mangled when transferred into a popular media obsessed with sensation, but this would then be a failure of journalism or science writing, rather than a failure of scientific integrity.

Adapted from Aeon

The Disappearing Physicist and His Elusive Particle

He ushered symmetry into theoretical physics, then vanished without a trace.

The members of the physics institute at Via Panisperna were in the habit of giving themselves jocular nicknames: Enrico Fermi was “The Pope,” Orso Corbino was “God the Almighty,” and Franco Rasetti was “The Cardinal Vicar.” It was 1930, and the Italian capital boasted a miraculous collection of scientists on their way to revolutionizing atomic and nuclear physics. Not since Galileo had Italy shown such scientific prominence. The team of mavericks became known as the “Via Panisperna Boys,” and was led by the now-celebrated Enrico Fermi, at the time in his 20s and already a full professor. But many of its other names will also sound familiar to present-day physics students: Wick, Racaha, Segrè, Pontecorvo…

As usually happens with such wondrous groups, it was born out of serendipity, the fortuitous confluence of talented people and visionary politicians. The latter came in the form of a Mafioso protector, Senator Corbino, who was powerful enough to keep science bureaucrats and Mussolini’s quirks at bay. Thus sheltered from the real world, the Boys did science in that atmosphere of pranks, jokes, and informality present in every high-intensity scientific establishment, an intellectual ambience popularized in “Surely You’re Joking, Mr. Feynman.” The Via Panisperna Institute was the sort of scientific kindergarten capable of nurturing truly creative thinking, where serious issues blended with bets on who could solve differential equations fastest. These, incidentally, were always won by “Il Grande Inquisitore”—Ettore Majorana.

Ettore Majorana was one of the oddballs of the group. A child prodigy, capable of doing cubic roots in his head as a kid, he carried into adulthood the concomitant problems in relating to others—and very pertinently to women—ensuring the prerequisite internal pool of frustrations essential for lateral thinking. Majorana was reared within a dysfunctional high-flying family, ruled over by an overbearing and domineering mother, who towered over his generation. He hailed from Sicily, a land well known for its artistic prowess, but also for an almost complete lack of scientific talent (not to mention an ingrained suspicion about science, and a preference for superstition). Later in life, already an established scientist, Majorana was quite unlike his colleagues, who typified the cliché of the scientist-philistine. Majorana was well versed in Pirandello and Schopenhauer, and had interests outside science beyond the standard-issue hobbies, particularly in literature and philosophy. He was what nowadays might be called a renaissance man.

After his family moved to Rome, Majorana enrolled in an engineering program, where he proved to be the ultimate nightmare for his teachers, given his ability to do mathematics in his head and spot inconsistencies at first sight. He was feared and respected by peers and professors alike, but he was also adrift, never studying or showing any interest in what he was supposed to be doing. In his early days, Einstein shared this aloofness, this disengagement from the world, before age and maturity brought about the massive explosion of creativity for which both became known. In Majorana's case his opportunity to flourish was served up on a silver tray, in the shape of Via Panisperna. Each of the Via Panisperna boys did both experimental and theoretical work, with the exception of Majorana, who never dirtied his hands in the lab. Majorana was more mathematically inclined, and contented himself with turning up late at the Institute, sitting aside, pointing out embarrassing errors "at sight," and then proposing theories that would hit the mainstream of physics only decades later. It was while installed in his niche as a feared out-of-the-box thinker within the Panisperna Boys that Majorana became interested in symmetry, and its central mathematical tool, group theory.

Particles and anti-particles are way too similar not to be related by symmetry. Consider the electron and the positron (or the anti-electron). Where they are not exactly identical (they have the same mass and spin) they are the precise opposite (for example, their electric charge has the same value but opposite sign). Years after Majorana, Richard Feynman and Ernst Stueckelberg were the first to understand that this uncanny similarity could be understood as a symmetry under the reversal of the arrow of time.

Suppose we started playing the film of the world backward in time. Within our human experience the result would be utter nonsense. Even children's stories would be preposterous: Having lived happily for ever before, one day the Prince would bestow a kiss upon the Princess, making her fall promptly into a deep coma, after which he'd forget about her and go hunting. Sleeping Beauty would then wake up at random years later near a spindle, followed by more incomprehensible garbage… what a lousy story for putting children to bed!

But for simple (as opposed to complex) physics systems the fairy tale would by and large remain unchanged. If we imagine a Solar System where all the velocities had been reversed, leading to a "backward in time" movie, it would all pretty much still work out. The length of the year for Earth and other planets would be the same. The sun would rise in the West and set in the East, but the duration of the day would be no different. Likewise, the world of sub-atomic particles undergoes remarkably simple changes under the reversal of the arrow of time. Specifically, particles are converted into anti-particles and vice versa.

When Majorana was active at Via Panisperna, the role of time-reversal in particle physics was not known and anti-particles, as they were then understood, brought with them a whole gamut of oddities. Paul Dirac had just discovered them a few years prior, in 1928, in a treatment that remains a historical peculiarity. He had set out to unify quantum mechanics and special relativity, and had discovered the simplest, rather than the most obvious group theory construction that did so. As a corollary it contained anti-matter. But in his theory the vacuum had to be defined as an infinite sea of particles with negative energy, and this infinite sea was postulated to be unobservable. The theory also predicted the creation and annihilation of particles of matter and anti-matter, but these processes were deemed esoteric and belonging to the realm of science fiction rather than real science. The community remained ambiguous about the success of Dirac's theory.

Majorana didn't like anti-particles either. His career started before they were experimentally discovered, and even before infinite vacuum seas and annihilations are considered, the nitty-gritty details of the mathematics of anti-particles displeased him. Scientists are often led by hunches and matters of taste: While we suppose that nature's beauty has a universal appeal, it is often first a gleam in the eye of the beholder. He therefore put all the weight of his not inconsiderable mathematical skills behind an attempt to circumvent the prediction of anti-matter. His agenda was to achieve the same unification that Dirac had achieved, between relativity and quantum mechanics, but without generating anti-particles.

The result would be the now-famous Majorana neutrino. Its construction was more complex than Dirac's, but also logically a far more obvious extension of existing theories. Where Dirac went for simplicity, Majorana went for logic minimalism. His new particle was its own anti-particle, and therefore did not require inventing any new anti-particles. It can be understood by blending the Feynman-Stueckelberg picture (which came after Majorana) with the idiosyncrasies of Schrödinger's cat. If quantum mechanics allows for the eerie superposition of a live and dead cat, it also permits the superposition of the two arrows of time. Cat and anti-cat can be folded into one, or to leave felines out of this, one may set up a perfectly symmetric superposition of neutrino and anti-neutrino. The Majorana neutrino travels both forward and backward in time, in equal amounts, and therefore remains unchanged if we play its film backward in time.

His new particle allowed Majorana to avoid the awkward aspects of Dirac's anti-world. If nature were as simple as possible, all particles should have been Majorana particles, and anti-particles would not exist. Nature, however, is what it is, and regarding the electron Dirac was right and Majorana wrong. The positron (or anti-electron) was discovered by Carl David Anderson in cosmic rays in 1933. But as Dirac himself once noted, it is often the case that "the opposite of a profound truth may well be another profound truth."

No one around Majorana even remotely understood what he was up to: the other Boys, for all their gifts, were much more down-at-heel. Like most physicists at the time, they regarded Majorana's constructions as pure mathematics, without any relevance to physics. Applying group theory to physical problems, as Majorana had done, was just embellishment, or as the English like to say, "over-egging the pudding."

Majorana didn't care. Part of his strength was a sense of self-deprecation with which he smeared everything he did; indeed he was even more negative about his own ideas than about the others.' He could try out unusual avenues because he didn't take himself seriously, and so wasn't constrained by a fear of failure. In a letter to a friend regarding his early efforts on symmetry and its toolbox, he said, "As for myself I do nothing sensible. That is, I study group theory with the firm intention of learning it, similar in this to that Dostoyevsky character who started one day to set aside his small change, fully persuaded that soon he'd be rich like Rothschild."
It was the beginning of a gradual and terminal estrangement from his colleagues.

Majorana was very bad at joining the usual science mafias that ensure a trouble-free career for any sensible scientist. Writer Leonardo Sciascia once said that Majorana "like all 'good' Sicilians" was averse to being a part of any group, or to establishing teams or partnerships. At Via Panisperna he was never properly one of the boys. It was for a good reason they called him The Grand Inquisitor. He spotted errors and deficiencies like no one else, and phrased his views as sharp and derogatory criticisms. People felt they were at the merciless hands of the Inquisition when he was nearby, and this took its toll in the resentment it induced in others.

But if he was critical of the others he was even tougher on himself. In his eyes his theories and ideas were never good enough. Self-deprecation is a difficult card to play—a bit of ego indulgence might have worked wonders in his darker moments. For years he'd exasperated everyone by having brilliant ideas but then refusing to publish them. In a community where "publish or perish" has always been the mantra, he couldn't care less about his article count. Where his colleagues were obsessed with priority disputes, he laughed them off.

Nor did it help that most people found him sad and depressive. His sense of humor was almost British—subtle but ultimately caustic and antiestablishment. He had serious problems making friends and was ultimately a loner. This was partly fallout from his child prodigy past, where he was paraded before visitors doing cubic roots in his head, and wasn't allowed to play with other kids so as to follow the demanding program of studies designed by his father. The line between Mozartian grandeur and child abuse can be very blurry indeed.

With regards to women, he suffered from an inferiority complex. As his friend Gaston Piqué said in an interview: "Because beautiful, properly, he wasn't; indeed, he was rather ugly. And… there was a girl… a very intelligent girl, and this young man, so prodigious, such a genius, truly attracted her. But he did nothing, even avoided her, because he was a victim of his inferiority complex…" As one of his relatives once stated: “Love would have made all the difference.” But it was not to be.

Something finally snapped inside Majorana around 1933. For the next four years, he would hardly leave his bedroom, requesting only a daily tray of food, which dwindled to little more than some milk. He had entered his own anti-world. This kind of behavior is not unusual in people who’ve fallen into severe depression. The Japanese coined a term for them: hikikomori, the modern-day hermits. Over his years of seclusion, family and friends just let him be. Any kind of treatment or counseling would have been an anachronism at that time, and he may not have even accepted it. Scientists and artists are famous for cherishing rather than resolving their hang-ups. Psychotherapy would have been seen as throwing the baby out with the bathwater. In the end both baby and bathwater were ejected from reality in a spectacular manner.

In January 1938 Majorana took up a professorship at Naples University. In what must have felt like a last-ditch effort to return to the world, he entered a prestigious academic competition, surprising everyone at Via Panisperna, who hadn’t heard from him for years. His entry included his now-famous paper on the Majorana particle. After some political contortions, related to his unusual circumstances, he was awarded a Chair “by exceptional merit.” At first, his life in Naples displayed a superficial semblance of normality. But a storm was brewing below the surface. It is hard to trace in depth his last three months, other than to glean a smattering of clues showing that things were actually going severely wrong on several fronts. There is even evidence that he fell in love with one of his students, a beautiful woman by the name of Gilda Senatore. It was unrequited love, that much is obvious. She was the last person to see him.

On the night of March 25, 1938, Majorana boarded a ship and was never seen again. He left behind a series of very odd notes, which may be perceived as suicide letters, but he also took with him the equivalent of $75,000 in present-day money as well as his passport. His body was never recovered. Over the years he was “sighted” on numerous occasions, leading to endless conspiracy theories. His psychology remains far more interesting, but less studied.

What has been most studied, and is today Majorana’s lasting legacy, is the mathematical formulation he left behind. Editions of Wigner’s masterpiece Group Theory and its Application to the Quantum Mechanics of Atomic Spectra start carrying references to Majorana from the 1940s onwards. But it was not until the 1960s that physicists started thinking of fundamental theories of nature in terms of symmetries and group theory, and Majorana’s full contribution was recognized. In 1982 Pontecorvo, one of the Via Panisperna boys, wrote “in the ’50s and in the ’60s the opinion was frequently expressed that neutrinos a la Majorana, although beautiful and interesting objects, are not realized in nature; … [things have changed] and the question raised by Majorana is now the central question in neutrino physics.” Soon afterward a massive international search for the Majorana neutrino started, focused on a process called neutrinoless double beta decay, which is an unambiguous hallmark of Majorana neutrinos. Nowadays this hunt involves about a dozen international collaborations combining the efforts of hundreds of physicists, and Majorana's name can be recognized in the acronym of many of them, such as NEMO (which stands for Neutrino Ettore Majorana Observatory).

Proving that neutrinos are Majorana particles would have dramatic implications for our understanding of symmetry in the natural world, and represents one of the final outstanding debates in the Standard Model of the elementary particles. A leading contender for next-generation particle model relies on supersymmetry, which posits that every fermion has a corresponding boson. Supersymmetry is more likely to be true if neutrinos are Majorana particles. In solid-state physics, too, mathematical analogues of Majorana particles are being studied and have already been found.

As for its creator, the riddle will never be broken. We are left with the story of a creator and a particle which are strangely parallel, the particle providing the perfect metaphor for its creator's eventual disappearance. On the outer wall of the house where Majorana was born, in Catania, a plaque reads: "His timid and solitary genius scrutinized and illuminated the secrets of the universe with the blaze of a meteor that too soon evaporated in March 1938, leaving us the mystery of his thinking." Majorana was only 31 years old at the time of departure. Or arrival, as the case may be.

Adapted from Nautilus

A Brief History of the Grand Unified Theory of Physics

It's the best of times or the worst of times in physics.

Particle physicists had two nightmares before the Higgs particle was discovered in 2012. The first was that the Large Hadron Collider (LHC) particle accelerator would see precisely nothing. For if it did, it would likely be the last large accelerator ever built to probe the fundamental makeup of the cosmos. The second was that the LHC would discover the Higgs particle predicted by theoretical physicist Peter Higgs in 1964 ... and nothing else.

Each time we peel back one layer of reality, other layers beckon. So each important new development in science generally leaves us with more questions than answers. But it also usually leaves us with at least the outline of a road map to help us begin to seek answers to those questions. The successful discovery of the Higgs particle, and with it the validation of the existence of an invisible background Higgs field throughout space (in the quantum world, every particle like the Higgs is associated with a field), was a profound validation of the bold scientific developments of the 20th century. However, the words of Sheldon Glashow continue to ring true: The Higgs is like a toilet. It hides all the messy details we would rather not speak of. The Higgs field interacts with most elementary particles as they travel through space, producing a resistive force that slows their motion and makes them appear massive. Thus, the masses of elementary particles that we measure, and that make the world of our experience possible is something of an illusion—an accident of our particular experience. As elegant as this idea might be, it is essentially an ad hoc addition to the Standard Model of physics—which explains three of the four known forces of nature, and how these forces interact with matter. It is added to the theory to do what is required to accurately model the world of our experience. But it is not required by the theory. The universe could have happily existed with massless particles and a long-range weak force (which, along with the strong force, gravity, and electromagnetism, make up the four known forces). We would just not be here to ask about them. Moreover, the detailed physics of the Higgs is undetermined within the Standard Model alone. The Higgs could have been 20 times heavier, or 100 times lighter. Why, then, does the Higgs exist at all? And why does it have the mass it does? (Recognizing that whenever scientists ask "Why?" we really mean "How?") If the Higgs did not exist, the world we see would not exist, but surely that is not an explanation. Or is it? Ultimately to understand the underlying physics behind the Higgs is to understand how we came to exist. When we ask, "Why are we here?," at a fundamental level we may as well be asking, "Why is the Higgs here?" And the Standard Model gives no answer to this question. Some hints do exist, however, coming from a combination of theory and experiment. Shortly after the fundamental structure of the Standard Model became firmly established, in 1974, and well before the details were experimentally verified over the next decade, two different groups of physicists at Harvard, where both Sheldown Glashow and Steven Weinberg were working, noticed something interesting. Glashow, along with Howard Georgi, did what Glashow did best: They looked for patterns among the existing particles and forces and sought out new possibilities using the mathematics of group theory. In the Standard Model the weak and electromagnetic forces of nature are unified at a high-energy scale, into a single force that physicists call the "electroweak force." This means that the mathematics governing the weak and electromagnetic forces are the same, both constrained by the same mathematical symmetry, and the two forces are different reflections of a single underlying theory. But the symmetry is "spontaneously broken" by the Higgs field, which interacts with the particles that convey the weak force, but not the particles that convey the electromagnetic force. This accident of nature causes these two forces to appear as two separate and distinct forces at scales we can measure—with the weak force being short-range and electromagnetism remaining long-range.

Georgi and Glashow tried to extend this idea to include the strong force, and discovered that all of the known particles and the three non-gravitational forces could naturally fit within a single fundamental symmetry structure. They then speculated that this symmetry could spontaneously break at some ultrahigh energy scale (and short distance scale) far beyond the range of current experiments, leaving two separate and distinct unbroken symmetries left over—resulting in separate strong and electroweak forces. Subsequently, at a lower energy and larger distance scale, the electroweak symmetry would break, separating the electroweak force into the short-range weak and the long-range electromagnetic force. They called such a theory, modestly, a Grand Unified Theory (GUT). At around the same time, Weinberg and Georgi along with Helen Quinn noticed something interesting—following the work of Frank Wilczek, David Gross, and David Politzer. While the strong interaction got weaker at smaller distance scales, the electromagnetic and weak interactions got stronger. It didn't take a rocket scientist to wonder whether the strength of the three different interactions might become identical at some small-distance scale. When they did the calculations, they found (with the accuracy with which the interactions were then measured) that such a unification looked possible, but only if the scale of unification was about 15 orders of magnitude in scale smaller than the size of the proton.

This was good news if the unified theory was the one proposed by Howard Georgi and Glashow—because if all the particles we observe in nature got unified this way, then new particles (called gauge bosons) would exist that produce transitions between quarks (which make up protons and neutrons), and electrons and neutrinos. That would mean protons could decay into other lighter particles, which we could potentially observe. As Glashow put it, "Diamonds aren't forever." Even then it was known that protons must have an incredibly long lifetime. Not just because we still exist almost 14 billion years after the big bang, but because we all don't die of cancer as children. If protons decayed with an average lifetime smaller than about a billion billion years, then enough protons would decay in our bodies during our childhood to produce enough radiation to kill us. Remember that in quantum mechanics, processes are probabilistic. If an average proton lives a billion billion years, and if one has a billion billion protons, then on average one will decay each year. There are a lot more than a billion billion protons in our bodies. However, with the incredibly small proposed distance scale and therefore the incredibly large mass scale associated with spontaneous symmetry breaking in Grand Unification, the new gauge bosons would get large masses. That would make the interactions they mediate be so short-range that they would be unbelievably weak on the scale of protons and neutrons today. As a result, while protons could decay, they might live, in this scenario, perhaps a million billion billion billion years before decaying. Still time to hold onto your growth stocks. With the results of Glashow and Georgi, and Georgi, Quinn, and Weinberg, the smell of grand synthesis was in the air. After the success of the electroweak theory, particle physicists were feeling ambitious and ready for further unification. How would one know if these ideas were correct, however? There was no way to build an accelerator to probe an energy scale a million billion times greater than the rest mass energy of protons. Such a machine would have to have a circumference of the moon's orbit. Even if it was possible, considering the earlier debacle over the Superconducting Super Collider, no government would ever foot the bill.

Happily, there was another way, using the kind of probability arguments I just presented that give limits to the proton lifetime. If the new Grand Unified Theory predicted a proton lifetime of, say, a thousand billion billion billion years, then if one could put a thousand billion billion billion protons in a single detector, on average one of them would decay each year. Where could one find so many protons? Simple: in about 3,000 tons of water.

So all that was required was to get a tank of water, put it in the dark, make sure there were no radioactivity backgrounds, surround it with sensitive phototubes that can detect flashes of light in the detector, and then wait for a year to see a burst of light when a proton decayed. As daunting as this may seem, at least two large experiments were commissioned and built to do just this, one deep underground next to Lake Erie in a salt mine, and one in a mine near Kamioka, Japan. The mines were necessary to screen out incoming cosmic rays that would otherwise produce a background that would swamp any proton decay signal. Both experiments began taking data around 1982–83. Grand Unification seemed so compelling that the physics community was confident a signal would soon appear and Grand Unification would mean the culmination of a decade of amazing change and discovery in particle physics—not to mention another Nobel Prize for Glashow and maybe some others. Unfortunately, nature was not so kind in this instance. No signals were seen in the first year, the second, or the third. The simplest elegant model proposed by Glashow and Georgi was soon ruled out. But once the Grand Unification bug had caught on, it was not easy to let it go. Other proposals were made for unified theories that might cause proton decay to be suppressed beyond the limits of the ongoing experiments. On Feb. 23, 1987, however, another event occurred that demonstrates a maxim I have found is almost universal: Every time we open a new window on the universe, we are surprised. On that day a group of astronomers observed, in photographic plates obtained during the night, the closest exploding star (a supernova) seen in almost 400 years. The star, about 160,000 light-years away, was in the Large Magellanic Cloud —a small satellite galaxy of the Milky Way observable in the southern hemisphere. If our ideas about exploding stars are correct, most of the energy released should be in the form of neutrinos, despite that the visible light released is so great that supernovas are the brightest cosmic fireworks in the sky when they explode (at a rate of about one explosion per 100 years per galaxy). Rough estimates then suggested that the huge IMB (Irvine- Michigan-Brookhaven) and Kamiokande water detectors should see about 20 neutrino events. When the IMB and Kamiokande experimentalists went back and reviewed their data for that day, lo and behold IMB displayed eight candidate events in a 10-second interval, and Kamiokande displayed 11 such events. In the world of neutrino physics, this was a flood of data. The field of neutrino astrophysics had suddenly reached maturity. These 19 events produced perhaps 1,900 papers by physicists, such as me, who realized that they provided an unprecedented window into the core of an exploding star, and a laboratory not just for astrophysics but also for the physics of neutrinos themselves.

Spurred on by the realization that large proton-decay detectors might serve a dual purpose as new astrophysical neutrino detectors, several groups began to build a new generation of such dual-purpose detectors. The largest one in the world was again built in the Kamioka mine and was called Super-Kamiokande, and with good reason. This mammoth 50,000-ton tank of water, surrounded by 11,800 phototubes, was operated in a working mine, yet the experiment was maintained with the purity of a laboratory clean room. This was absolutely necessary because in a detector of this size one had to worry not only about external cosmic rays, but also about internal radioactive contaminants in the water that could swamp any signals being searched for.

Meanwhile, interest in a related astrophysical neutrino signature also reached a new high during this period. The sun produces neutrinos due to the nuclear reactions in its core that power it, and over 20 years, using a huge underground detector, physicist Ray Davis had detected solar neutrinos, but had consistently found an event rate about a factor of three below what was predicted using the best models of the sun. A new type of solar neutrino detector was built inside a deep mine in Sudbury, Canada, which became known as the Sudbury Neutrino Observatory (SNO).
Super-Kamiokande has now been operating almost continuously, through various upgrades, for more than 20 years. No proton-decay signals have been seen, and no new supernovas observed. However, the precision observations of neutrinos at this huge detector, combined with complementary observations at SNO, definitely established that the solar neutrino deficit observed by Ray Davis is real, and moreover that it is not due to astrophysical effects in the sun but rather due to the properties of neutrinos. The implication was that at least one of the three known types of neutrinos is not massless. Since the Standard Model does not accommodate neutrinos' masses, this was the first definitive observation that some new physics, beyond the Standard Model and beyond the Higgs, must be operating in nature.

Soon after this, observations of higher-energy neutrinos that regularly bombard Earth as high-energy cosmic-ray protons hit the atmosphere and produce a downward shower of particles, including neutrinos, demonstrated that yet a second neutrino has mass. This mass is somewhat larger, but still far smaller than the mass of the electron. For these results team leaders at SNO and Kamiokande were awarded the 2015 Nobel Prize in Physics—a week before I wrote the first draft of these words. To date these tantalizing hints of new physics are not explained by current theories.

The absence of proton decay, while disappointing, turned out to be not totally unexpected. Since Grand Unification was first proposed, the physics landscape had shifted slightly. More precise measurements of the actual strengths of the three non-gravitational interactions—combined with more sophisticated calculations of the change in the strength of these interactions with distance—demonstrated that if the particles of the Standard Model are the only ones existing in nature, the strength of the three forces will not unify at a single scale. In order for Grand Unification to take place, some new physics at energy scales beyond those that have been observed thus far must exist. The presence of new particles would not only change the energy scale at which the three known interactions might unify, it would also tend to drive up the Grand Unification scale and thus suppress the rate of proton decay—leading to predicted lifetimes in excess of a million billion billion billion years. As these developments were taking place, theorists were driven by new mathematical tools to explore a possible new type of symmetry in nature, which became known as supersymmetry. This fundamental symmetry is different from any previous known symmetry, in that it connects the two different types of particles in nature, fermions (particles with half-integer spins) and bosons (particles with integer spins). The upshot of this is that if this symmetry exists in nature, then for every known particle in the Standard Model at least one corresponding new elementary particle must exist. For every known boson there must exist a new fermion. For every known fermion there must exist a new boson. Since we haven't seen these particles, this symmetry cannot be manifest in the world at the level we experience it, and it must be broken, meaning the new particles will all get masses that could be heavy enough so that they haven't been seen in any accelerator constructed thus far. What could be so attractive about a symmetry that suddenly doubles all the particles in nature without any evidence of any of the new particles? In large part the seduction lay in the very fact of Grand Unification. Because if a Grand Unified theory exists at a mass scale of 15 to 16 orders of magnitude higher energy than the rest mass of the proton, this is also about 13 orders of magnitude higher than the scale of electroweak symmetry breaking. The big question is why and how such a huge difference in scales can exist for the fundamental laws of nature. In particular, if the Standard Model Higgs is the true last remnant of the Standard Model, then the question arises, Why is the energy scale of Higgs symmetry breaking 13 orders of magnitude smaller than the scale of symmetry breaking associated with whatever new field must be introduced to break the GUT symmetry into its separate component forces? The problem is a little more severe than it appears. When one considers the effects of virtual particles (which appear and disappear on timescales so short that their existence can only be probed indirectly), including particles of arbitrarily large mass, such as the gauge particles of a presumed Grand Unified Theory, these tend to drive up the mass and symmetry-breaking scale of the Higgs so that it essentially becomes close to, or identical to, the heavy GUT scale. This generates a problem that has become known as the naturalness problem. It is technically unnatural to have a huge hierarchy between the scale at which the electroweak symmetry is broken by the Higgs particle and the scale at which the GUT symmetry is broken by whatever new heavy field scalar breaks that symmetry.

The mathematical physicist Edward Witten argued in an influential paper in 1981 that supersymmetry had a special property. It could tame the effect that virtual particles of arbitrarily high mass and energy have on the properties of the world at the scales we can currently probe. Because virtual fermions and virtual bosons of the same mass produce quantum corrections that are identical except for a sign, if every boson is accompanied by a fermion of equal mass, then the quantum effects of the virtual particles will cancel out. This means that the effects of virtual particles of arbitrarily high mass and energy on the physical properties of the universe on scales we can measure would now be completely removed. If, however, supersymmetry is itself broken (as it must be or all the supersymmetric partners of ordinary matter would have the same mass as the observed particles and we would have observed them), then the quantum corrections will not quite cancel out. Instead they would yield contributions to masses that are the same order as the supersymmetry-breaking scale. If it was comparable to the scale of the electroweak symmetry breaking, then it would explain why the Higgs mass scale is what it is. And it also means we should expect to begin to observe a lot of new particles—the supersymmetric partners of ordinary matter—at the scale currently being probed at the LHC.

This would solve the naturalness problem because it would protect the Higgs boson masses from possible quantum corrections that could drive them up to be as large as the energy scale associated with Grand Unification. Supersymmetry could allow a "natural" large hierarchy in energy (and mass) separating the electroweak scale from the Grand Unified scale. That supersymmetry could in principle solve the hierarchy problem, as it has become known, greatly increased its stock with physicists. It caused theorists to begin to explore realistic models that incorporated supersymmetry breaking and to explore the other physical consequences of this idea. When they did so, the stock price of supersymmetry went through the roof. For if one included the possibility of spontaneously broken supersymmetry into calculations of how the three non-gravitational forces change with distance, then suddenly the strength of the three forces would naturally converge at a single, very small-distance scale. Grand Unification became viable again!

Models in which supersymmetry is broken have another attractive feature. It was pointed out, well before the top quark was discovered, that if the top quark was heavy, then through its interactions with other supersymmetric partners, it could produce quantum corrections to the Higgs particle properties that would cause the Higgs field to form a coherent background field throughout space at its currently measured energy scale if Grand Unification occurred at a much higher, superheavy scale. In short, the energy scale of electroweak symmetry breaking could be generated naturally within a theory in which Grand Unification occurs at a much higher energy scale. When the top quark was discovered and indeed was heavy, this added to the attractiveness of the possibility that supersymmetry breaking might be responsible for the observed energy scale of the weak interaction.

All of this comes at a cost, however. For the theory to work, there must be two Higgs bosons, not just one. Moreover, one would expect to begin to see the new supersymmetric particles if one built an accelerator such as the LHC, which could probe for new physics near the electroweak scale. Finally, in what looked for a while like a rather damning constraint, the lightest Higgs in the theory could not be too heavy or the mechanism wouldn't work.

As searches for the Higgs continued without yielding any results, accelerators began to push closer and closer to the theoretical upper limit on the mass of the lightest Higgs boson in supersymmetric theories. The value was something like 135 times the mass of the proton, with details to some extent depending on the model. If the Higgs could have been ruled out up to that scale, it would have suggested all the hype about supersymmetry was just that.

Well, things turned out differently. The Higgs that was observed at the LHC has a mass about 125 times the mass of the proton. Perhaps a grand synthesis was within reach. The answer at present is ... not so clear. The signatures of new super-symmetric partners of ordinary particles should be so striking at the LHC, if they exist, that many of us thought that the LHC had a much greater chance of discovering supersymmetry than it did of discovering the Higgs. It didn't turn out that way. Following three years of LHC runs, there are no signs of supersymmetry whatsoever. The situation is already beginning to look uncomfortable. The lower limits that can now be placed on the masses of supersymmetric partners of ordinary matter are getting higher. If they get too high, then the supersymmetry-breaking scale would no longer be close to the electroweak scale, and many of the attractive features of supersymmetry breaking for resolving the hierarchy problem would go away. But the situation is not yet hopeless, and the LHC has been turned on again, this time at higher energy. It could be that supersymmetric particles will soon be discovered. If they are, this will have another important consequence. One of the bigger mysteries in cosmology is the nature of the dark matter that appears to dominate the mass of all galaxies we can see. There is so much of it that it cannot be made of the same particles as normal matter. If it were, for example, the predictions of the abundance of light elements such as helium produced in the big bang would no longer agree with observation. Thus physicists are reasonably certain that the dark matter is made of a new type of elementary particle. But what type? Well, the lightest supersymmetric partner of ordinary matter is, in most models, absolutely stable and has many of the properties of neutrinos. It would be weakly interacting and electrically neutral, so that it wouldn't absorb or emit light. Moreover, calculations that I and others performed more than 30 years ago showed that the remnant abundance today of the lightest supersymmetric particle left over after the big bang would naturally be in the range so that it could be the dark matter dominating the mass of galaxies.

In that case our galaxy would have a halo of dark matter particles whizzing throughout it, including through the room in which you are reading this. As a number of us also realized some time ago, this means that if one designs sensitive detectors and puts them underground, not unlike, at least in spirit, the neutrino detectors that already exist underground, one might directly detect these dark matter particles. Around the world a half dozen beautiful experiments are now going on to do just that. So far nothing has been seen, however.

So, we are in potentially the best of times or the worst of times. A race is going on between the detectors at the LHC and the underground direct dark matter detectors to see who might discover the nature of dark matter first. If either group reports a detection, it will herald the opening up of a whole new world of discovery, leading potentially to an understanding of Grand Unification itself. And if no discovery is made in the coming years, we might rule out the notion of a simple supersymmetric origin of dark matter—and in turn rule out the whole notion of supersymmetry as a solution of the hierarchy problem. In that case we would have to go back to the drawing board, except if we don't see any new signals at the LHC, we will have little guidance about which direction to head in order to derive a model of nature that might actually be correct. Things got more interesting when the LHC reported a tantalizing possible signal due to a new particle about six times heavier than the Higgs particle. This particle did not have the characteristics one would expect for any supersymmetric partner of ordinary matter. In general the most exciting spurious hints of signals go away when more data are amassed, and about six months after this signal first appeared, after more data were amassed, it disappeared. If it had not, it could have changed everything about the way we think about Grand Unified Theories and electroweak symmetry, suggesting instead a new fundamental force and a new set of particles that feel this force. But while it generated many hopeful theoretical papers, nature seems to have chosen otherwise.

The absence of clear experimental direction or confirmation of supersymmetry has thus far not bothered one group of theoretical physicists. The beautiful mathematical aspects of supersymmetry encouraged, in 1984, the resurrection of an idea that had been dormant since the 1960s when Yoichiro Nambu and others tried to understand the strong force as if it were a theory of quarks connected by string-like excitations. When supersymmetry was incorporated in a quantum theory of strings, to create what became known as superstring theory, some amazingly beautiful mathematical results began to emerge, including the possibility of unifying not just the three non-gravitational forces, but all four known forces in nature into a single consistent quantum field theory. However, the theory requires a host of new spacetime dimensions to exist, none of which has been, as yet, observed. Also, the theory makes no other predictions that are yet testable with currently conceived experiments. And the theory has recently gotten a lot more complicated so that it now seems that strings themselves are probably not even the central dynamical variables in the theory. None of this dampened the enthusiasm of a hard core of dedicated and highly talented physicists who have continued to work on superstring theory, now called M-theory, over the 30 years since its heyday in the mid-1980s. Great successes are periodically claimed, but so far M-theory lacks the key element that makes the Standard Model such a triumph of the scientific enterprise: the ability to make contact with the world we can measure, resolve otherwise inexplicable puzzles, and provide fundamental explanations of how our world has arisen as it has. This doesn't mean M-theory isn't right, but at this point it is mostly speculation, although well-meaning and well-motivated speculation. It is worth remembering that if the lessons of history are any guide, most forefront physical ideas are wrong. If they weren't, anyone could do theoretical physics. It took several centuries or, if one counts back to the science of the Greeks, several millennia of hits and misses to come up with the Standard Model. So this is where we are. Are great new experimental insights just around the corner that may validate, or invalidate, some of the grander speculations of theoretical physicists? Or are we on the verge of a desert where nature will give us no hint of what direction to search in to probe deeper into the underlying nature of the cosmos? We'll find out, and we will have to live with the new reality either way.

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