The Science We Trust

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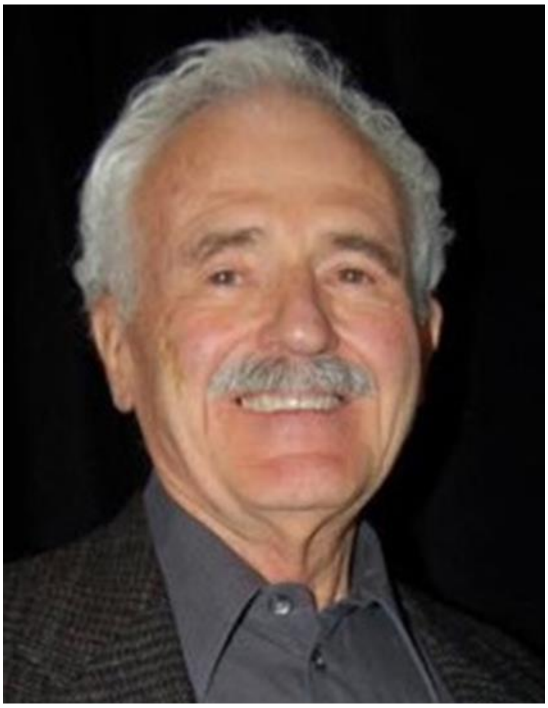

CHRIS ENKE is a chemist who has been on faculty at Princeton, Michigan State University, and the University of New Mexico. He has emeritus professor status at the latter two institutions. His BA degree in chemistry is from Principia College Illinois; he has MS and PhD degrees in chemistry from the University of Illinois, Champaign/Urbana.

He co-invented the method of ion fragmentation used in tandem (MS/MS) mass spectrometers which is a key instrument of biomedical science. He has received awards from the *American Society for Mass Spectrometry* and the *American Chemical Society*. He has authored over a dozen patents and hundreds of peer-reviewed articles and book chapters. He coauthored *Electronics for Scientists* with sequels and wrote *The Art and Science of Chemical Analysis*.

Teaching has been his ambition and passion since grade school and continues to be in retirement. His interest in the deeper meaning of scientific research stemmed from reading *Zen and The Art of Motorcycle Maintenance* (Pirsig 1974). Poincare's point about there being multiple plausible explanations for any given set of observations piqued his interest in the philosophy of science. The harmful effects of science denial further fueled his study aiming at finding a logical basis for certainty in the parts of science that undergird technology. This Opinion Piece encapsulates his conclusions. They are ideas he wishes he had known while still teaching and mentoring.

More details at: www.chrisenke.net.

The Science We Can (and Do) Trust

I am not a credentialed philosopher. But my work in science has made me aware of the cognitive dissonance between a) the accepted dogma that all current science may someday be disproved and b) the fact that we depend on technology in nearly every aspect of our lives. On one hand, the history of theories disproved and the impossibility of predicting the future have led to the conclusion that nothing we know now is certain to remain valid. But we don't act like it's all up for grabs. We trust science-based technology to keep our vehicles running, our planes flying, our cellphones communicating. We rely on these and countless other devices for health, comfort, work, and entertainment. We don't worry about waking up to find that a crucial device no longer works because a law it is based on has been disproved.

In my work, I assumed the laws I used in research and taught in the classroom were sound. But as distrust in science, unassuaged by our failure to claim plausible certainty, has become an increasingly harmful social phenomenon, I looked for solid arguments to counter this trend in the philosophy of science—an inquiry that has intensified in my retirement years. This effort has finally, for me, led to the identification of the parts of science we know for sure and why that is so. It has also clarified which parts of our current knowledge are subject to change and disproof.

The three pillars supporting the conclusion that nothing scientists claim today is certain to remain valid are:

1. History is rife with the shards of scientific theories proven wrong. How can we be certain that this time we're right?
2. Consistency is no proof of certainty. An exception to any regularity or uniformity (*i.e.*, law) could be found at any time.
3. Our 'simple' laws do not apply in the real world where multiple factors can affect the outcome.

I propose that the narrative of comprehensive uncertainty is a myth—that there are logical responses to these pillars of doubt. While universal truths are still elusive, many philosophers (the realists) agree there must be some things we know for sure. If that weren't so, science would not be so successful. But which things? This question has been addressed in several stages over centuries. Putting the pieces of this puzzle together, *each of them suggested by others*, has led to a satisfying and logical conclusion.

The trace that remains

The first pillar of scientific uncertainty is the number of missteps science has had along the way. An early example is the notion of a geocentric solar system. But misconceptions continue throughout history. Lavoisier proposed that the transfer of heat is due to the motion of a caloric fluid, Becher explained combustion as the release of a substance called phlogiston, Boyle and Huygens supported the notion that light waves would require a medium they called the luminous aether, and Einstein believed, until astronomers revealed the red-shift in absorption and emission spectra from distant galaxies, that the universe was static.

In each of the above case, later data made those explanations untenable. Given that track record, one would naturally suspect that a contrary observation might undo any of our current theories.

But that conclusion has long bothered scientists and philosophers who believed that at least some knowledge must be certain. If a theory has worked and made accurate predictions, how can it be completely wrong? In the 19th century, Henri Poincaré wrote on what he called "the trace that remains" of disproved theories. He looked at them and found the part that remains valid is within the laws[1], (statements of relationships) such as the Newton's gravitational equation $F = Gm_1m_2/d^2$, or water freezes at 0° C. He believed that no matter what we learned about the nature of phenomena (the nature of gravity or the structure of water), experimentally confirmed laws would continue to work. In other words, part of a theory can be revised or disproved while another part remains valid.

Reading Poincaré's writings on this point was encouraging. Though not a complete answer, I began to see that later theories would have to accommodate the confirmed data on which the earlier theory was based. And further, that many equations based on those data would also still work, even if replaced by better versions. For example, the geocentric equations for planetary position still work as well as they did when derived.

Besides giving us a clue on where to look for certainty, Poincaré's thoughts imply another essential aspect of scientific knowledge which is that *a scientific theory or concept has two distinct elements*. One of them is our confirmed observations of how factors are related, *i.e.*, our *laws*. The other is our *explanation* of the laws—why they work that way[2]. The equations and relationships are the functional part of a theory, enabling the prediction of outcomes. The explanation, the part that may change as we learn more, links with other explanations in the fabric of scientific knowledge.

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[1] H. Poincaré, 'The Value of Science'. In *The Foundations of Science.* (1913) (Academia Renascens, 2021) p.352.

[2] H. Margenau, *The Nature of Physical Reality, a Philosophy of Modern Physics*. (McGraw-Hill, New York, reprinted Ox Bow Press, Woodbridge, 1977) p. 448.

Scientific realists including Worrall[3], Putnam[4], and Ladyman[5], have extended Poincaré's thoughts. They argue that the success of science would be a miracle were there not some aspects that represent reality. In fact, one definition of the word '[miracle]' is "an event that is inexplicable by natural or scientific laws.

Imagine this: *You have just opened the latest issue of* Science *magazine to read that studies have shown that electrical conduction can occur without the physical movement of charge carriers, thus challenging a premise of Ohm's theory of conduction. If confirmed, all electrical and electronic devices based on Ohm's law may become non-functional. Meanwhile, caution is advised while using anything electronic.*

You know that the above scenario would not happen because a different understanding of the mechanism of electrical conduction will not change the observations Ohm's Law is based on nor the reliability of devices designed using it. So there are things we know for sure and can count on to remain valid even after the original premise or explanation part of the theory changes. As we've said, these certainties will be found among the laws scientific research and technological applications are based on. But this does not resolve the problems of potential exceptions and the complexities of the what and the why of scientific theories.

The what and why of scientific theories

In the previous section, we saw that a scientific theory has two parts, the *law* or statement of relationship and the *explanation* for why nature acts this way. This is one of those concepts that is obvious, but not simple. The confusion comes from our tendency to merge these two aspects of knowledge in our minds. "This happens because…" When we use the word theory, such as Einstein's Special Theory of Relativity, we mean both the hypotheses from which it was developed and the equations that he derived from them. They are as linked in our minds as the two sides of a coin.

Even though interdependent, a law and its explanation serve distinct purposes and have unique characteristics. Laws do the work. We use equations or logical statements to predict the outcomes of natural phenomena. Laws are generally quantitative. In science classes, we applied laws to solve the problem sets and tested their power of prediction in the lab. Then, on the job, scientists and engineers use them in the design of experiments and practical devices. The laws tell us 'what' but give us no information as to 'why.'

Some laws are developed by adopting a premise and developing the consequences of that assumption. Einstein began by assuming the speed of light is the same regardless of the relative motion of the source and the observer. From this, he predicted the phenomenon of time dilation on moving objects. Such theoretically derived relationships can become laws when observations bear them out.

But more often, scientists form laws by developing an expression that generalizes a set of observations. Boyle measured the pressure of a constant amount of gas at different volumes and found that P times V is a constant. Early astronomers developed equations from which they could calculate the future positions of the planets. I have developed laws both ways, by solving the mathematical consequences of a hypothesis and finding it fit data in the literature[6] and by searching for a relationship that would meet my experimental goals[7],[8]. In either case, laws are confirmed by the consistent success of their predictions.

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[3] J. Worrall, *Miracles, Pessimism and Scientific Realism*, *PhilArchive*, https://philarchive.org/rec/WORMPA

[4] H. Putnam, *Mathematics, Matter and Method* (: Cambridge University Press, Cambridge 1975) p.73.

[5] J. Ladyman, 'What is Structural Realism?' *Studies in History and Philosophy of Science*, **29**: pp. 409–424.

[6] Enke, C. G. *Anal. Chem*. **69**, 4885-93 (1997).

[7] Enke, C. G. Christie G. Enke* and Gareth S Dobson, *Anal. Chem*. **79**. 8650-8661 (2007).

[8] Christie G. Enke and Luc J. Nagels *Anal. Chem*. **83**. 2539-2546 (2011).

However, not having a plausible explanation for a phenomenon is problematic. We have a need to make sense of it. And this is not just true for scientists. As Hofstadter and Sandler say[9], “At every moment of our lives, our concepts are selectively triggered by analogies that our brain makes without let-up to make sense of the new and unknown in terms of the old and known.” In other words, we automatically seek an association between what we see and why it happens that way.

An observation is presumably something that actually happened; the associated explanation is our attempt to connect it with other things we ‘know’. It is the explanation that can change as we advance our study of the phenomenon.

Explanations, even though potentially tentative, play an essential role. As analogies or metaphors, they help us imagine or picture the phenomenon, they suggest other aspects of the phenomenon that we can then look for, and they add to the fabric of scientific knowledge through their links to other explanations. *Their value is not in their truth but in their usefulness*[10].

If we do not consider the law and its explanation separately, we can, and often have, declared the whole theory or concept invalid when it is just the explanation that has been disproved. The previously validated relationships continue to work as well as before.

The Black Swan

We now address the second pillar of science uncertainty, *i.e.*, consistency is not certainty. The black swan is the iconic example of the argument that no matter how consistent a set of observations, the possibility of an exception cannot be ruled out. Since only white swans were known in Europe, Europeans could confidently say, “all swans are white.” This uniformity was upset in 1836, when a Dutch sailor sighted black swans in the waters of Western Australia. Rephrasing the lesson this anomaly teaches, James Thurber quipped, “There is no exception to the rule that every rule has an exception.”

Philosophers from David Hume on have repeated the assertion ‘there is no guarantee against a contrary observation’ to a scientific law. Karl Popper emphasized this point suggesting that scientists should look for conditions in which accepted laws might fail. Popper referred to such conditions as ‘falsifications’ with the implication that such exceptions weaken or invalidate a law.

But do they? If they did, most of our widely used laws would be weak and undependable. Take a few examples: light travels in a straight line *unless* passing a mass that distorts space, water freezes at 0 ºC *if* it is free of dissolved substances, the gas law is only accurate *for ideal* gases, and so on. In fact, most of the scientific laws we apply routinely have conditions that are exceptions to their applicability[11]. But scientists take those conditions into account, treating them as *limits* or boundaries on a law’s applicability. These limits prevent laws from being universally true.

But the essential point is, *we can trust verified laws to continue to work within their tested limits*. It has been said that Einstein’s relativity has proven Newton’s laws to be wrong[12]. If so, why do we still teach and use them? It’s because what Einstein found was not a revocation of Newton’s laws, but a limit or boundary on their accurate application[13]. He found a condition in which they don’t apply. Except for objects with relativistic velocities, our applications of Newton’s laws have not changed. So conditions which are exceptions do not

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[9] D. Hofstadter, Douglas, I. Sander, Surfaces and Essences, Analogy as the Fuel and Fire of Thinking (Basic Books, New York, 2013) p. 3

[10] Yucel, Robyn, *Science & Education*, 27, 407-413, 2018.

[11] A. Potochnik, *Idealization and the Aims of Science*, (The University of Chicago Press, Chicago and London, 2017) p.19.

[12] M. Strevens, *The Knowledge Machine, How Irrationality Created Modern Science* (Liverright Publishing, New York, London, 2020) p. 111.

[13] T. Kuhn, *The Structure of Scientific Revolutions, 3rd ed*, (University of Chicago Press, Chicago, London, 1962) p.99

discredit a law, they just define a limit on its accurate application.

The discovery of a new limit to a law arises from an observation of its failure *under previously untested conditions*. The addition of a new boundary does not affect the reliability of a law within its previously known limits. Instead, it adds to our knowledge of the phenomenon. A new limit might reveal an unexpected phenomenon to study[14] or drive a field in a new direction.

I would rephrase David Hume's point that we cannot assume that any uniformity will apply over all time and space to "the conditions under which a law has been tested, which are necessarily limited, define the range of the law's assured applicability." Since testing under all conditions is impossible, *no law can confidently be assumed to be a universality*[15,16].

Many have recognized that laws are dependable within the range of tested conditions. Mariano Artigas, a Spanish physicist and philosopher, using the word 'stipulation' rather than 'limit' said[17], "It is possible to achieve inter-subjective formulations and demonstrations based on… stipulations that restrict the domain of consideration." In other words, the acknowledgement of limits and the empirical affirmation of reality within those limits resolves the no-miracles quandary and supplies the assurance we have been looking for. Unfortunately, he did not develop this insight further. Others have, but with highly restrictive caveats.

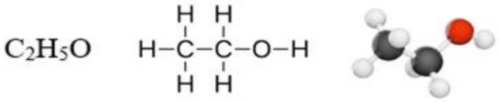
For example, Erica Thompson[18], says that some models "can do extremely well" where "the observations do not stray much outside the data used to generate the models." While acknowledging the usefulness of some laws (which here she is calling models), her implication is that such instances of reliability are 'special.' I disagree.

Most of the laws we use have a range of tested conditions that is broad enough to make them useful. If that were not so, our technological devices would require controlled environments in which to work. There would be no TVs, airplanes, or cellphones.

The picture and the thing

This picture by the surrealist Rene Magritte, is humorously but astutely titled, "This is not a pipe." He is not gas-lighting; he's saying that a picture of a pipe is not a pipe. For me, this beautifully illustrates a core characteristic of scientific explanations. They help us 'picture' or 'imagine' a phenomenon, but they are not the phenomenon.

For a scientific example, consider these representations of the molecule ethanol.



The first gives the chemical composition in terms of the number of atoms for each element. From this and tables of the characteristics of the elements we can calculate the molecular weight and the weights of all the

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[14] F. Wilczek, A Beautiful Question, Finding Nature's Deep Design (Penguin Books, New York, 2015) p. 203.

[15] A. Potochnik, *Idealization and the Aims of Science*, (The University of Chicago Press, Chicago and London, 2017) P. 25.

[16] N. Cartwright, *The Dappled World, A Study of the Boundaries of Science* (Cambridge University Press, 1999) p.4.

[17] A. Mariano, *Knowing Things for Sure, Science and Truth* (University Press of America, Lanham, Oxford, 2006), p. 202.

[18] Erica Thompson, *Escape from Model Land*, (Basic Books, New York 2022) p. 26.

isotopes. The structural diagram shows how the atoms and their bonds are arranged. From it, we can see the alkane and hydroxyl groups by which we can explain how ethanol is soluble in both water and hexane. And in the stick model, we can see the tetrahedral distribution of the carbon bonds and the 104.5º angle of the oxygen bond.

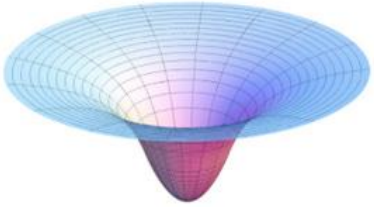
But none of these representations of ethanol reveal or explain all its characteristics, nor is it possible to do so in a single figure. There are the vibrational and rotational frequencies of the bonds and their strengths, liquid ethanol's boiling and freezing temperatures, the optical absorptivities in the liquid and gaseous states, and so on and on. Each of these has its own set of laws and the explanations for them.

So, there are many representations of ethanol, and each is far from being complete. Further, the qualities of ethanol that are significant, and the ways they are meaningful, differ for the organic chemist, the spectroscopist, and the physiologist. Meanwhile, ethanol molecules, with all their known and yet-to-be-revealed qualities, just are what they are and do what they do.

Even though incomplete, only analogous in specific ways, and subject to revision, the many ways we 'picture' phenomena can be extremely helpful. As Erica Thompson says in her recent book[19],

> When you create a metaphor, or model or meme, you are reframing a situation … .so that we can see it from a new perspective, make unexpected links, and create stories and explanations that help us think collectively, as well as individually about the implications of the information we have.

Take the concept of the sun's mass distorting the space around it as shown in this geometric diagram:



With this illustration, we can readily imagine circular orbits of the planets maintain their path along a circular line because of their momentum. We can even see how tilting that path would produce the more commonly found elliptical orbits. And thinking of a similar distortion around the mass of the earth we can imagine the paths of our satellites, real and artificial, and how an object separated from the earth and lacking a satellite's orbital momentum will fall. Then, placing the space distortion diagrams for the earth and sun on the same plot, one can find the point where their attraction is equal, the ingenious location chosen for the remarkable James Webb Space Telescope.

Furthermore, analogies have often been central in the formation of scientific breakthroughs. Think of the Doppler effect, known to occur with sound, but imagined applying to light beams as well from which we deduce the red shift in light from distant galaxies.

Because the explanation of a phenomenon is not the phenomenon, but a model or analogy, there could be more than one credible and useful explanation. In fact, both Poincare[20] and Einstein[21] have said that there can be many reasonable explanations for a law or a set of observations. Our imagination may only present one or two, but we should not stop conceiving others as soon as we have one that makes sense. There may be others that do even better or are more useful in certain contexts.

Two stories of 'problematic' data

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[19] Thompson, Erica, Escape from Model Land, Basic Books, New York, 2022, pp.31 and 45.

[20] Poincaré, Henri, *Science and Hypothesis*, First English translation, Walter Scott, London, 1905. My copy is the Dover edition, 1952. p. 167.

[21] Albert Einstein, *Induction and Deduction in Physics*, *Berliner Tageblatt*, 25 December 191.

Once aware of the two aspects of scientific knowledge, the verified laws and the sense we make of them, it is fascinating to see what happens when new data is inconsistent with a current explanation, *i.e*., our understanding of the phenomenon. The process by which this is sorted out is often at the heart of the tale. This section includes two such stories—the first in which a contrary observation was found to be erroneous and the other in which a fortuitous observation disproved an explanation.

Neutrinos were known to travel at the speed of light in space and they were known to pass, with equal ease, through the earth. A detector at the Laboratori Nazionali del Gran Sasso in Abruzzo, Italy was set up to receive neutrinos generated at CERN in Geneva, Switzerland. In 2011, an experiment was set up to study the shift in neutrino states as they traveled 731 km. Dario Autiero realized that this same apparatus could be used to measure the neutrino's speed through so much granite. It was this ancillary experiment that made the news.

The reason for its notoriety was that the neutrinos appeared to negotiate that distance some 63 ns (That's 6.3 percent of a millionth of a second) quicker than light would take through free space. If true, this would upset a basic tenet of Einstein's special theory of relativity and have far-reaching implications. Roughly nine months later, two sources of error in the equipment measuring the interval between generation and detection were discovered. The neutrinos had flown at exactly the speed of light, and theoretical physicists could finally exhale.

For a few months, it seemed this could be the moment Einstein anticipated when he said that no experiment could prove him right, but a single experiment could prove him wrong. But would he have been completely wrong?

Strong gravitational fields would still bend the path of light rays, e would still equal mc^2, and time dilation on moving objects would still occur to the same degree. If the premise used by Einstein in his derivation was wrong, a different one would be sought. Again, the laws would remain valid, a revised explanation would be pursued, and new limits might be found.

The implications of an explanation can itself stimulate the discovery of new laws. That has notably been the case in Einstein's theories of relativity. Their predictions are still being tested, and in every case so far, they have been confirmed. The prediction of gravitational lensing, for example, has now become a major tool of astronomical observation.

The second story also involves an observation that upset an accepted explanation. This time, the explanation was not just wrong; it was blocking progress. In the early days of computerizing scientific instruments, I wanted to build an analytical device that would separate and then identify components in a mixture under computer control. With my graduate student, Rick Yost, we chose quadrupole mass analyzers for both functions. The charged molecules (called ions) whose mass had been selected by the first quadrupole would then be fragmented so its distinctive pattern of fragment masses, as seen by the second quadrupole, would provide identification.

Tandem mass-selection stages (using magnetic and electric sectors) were already used to study ion fragmentation by energetic collision with gas molecules. These studies, which used ion accelerations of thousands of volts, showed that fragmentation efficiency quickly declined from poor to non-existent as the ion acceleration voltage decreased.

The efficiency at various levels of acceleration had been fit to an equation and an explanation for the observation developed. It was that an electron in the ion to be fragmented was excited by a near encounter with a collision gas molecule. This energy then moved to a chemical bond and caused its rupture. Lower ion velocities did not induce enough energy to break a bond.

The "required" ion acceleration energy for fragmentation was a hundred times higher than those used with quadrupole analyzers. If collisional fragmentation wouldn't work, what could we use? A chance discussion with Jim Morrison broke the ice. He was studying laser excitation to fragment ions. And, just as we had envisioned our instrument, he used one quadrupole analyzer to select the ions to fragment and the other to find the fragment masses.

Would photofragmentation work for us? Jim said no, because its efficiency was so poor his laser-produced fragments were drowned out by continuously produced background fragments.

We puzzled over what process could be producing the interfering fragments. And if we found out, could we use it in our instrument? Contrary to the accepted mechanism for ion fragmentation, experiments in Morrison's lab proved his "noise" fragments were formed by low-energy collisions with sparse gas molecules. Jim had placed an ion-containment chamber between his two analyzers to enable the transfer of fragments to the second analyzer.

Thus was born the triple-quadrupole mass spectrometer, the precursor of a myriad succession of 'MS/MS' instruments that have revolutionized the role of mass spectrometry in chemical analysis. Their evolution continues some fifty years after their introduction and their invention was the subject of an *Association of Biomedical Research Facilities* award in March 2023.

Two factors stood in the way of this discovery. One was the incorrect explanation the sector mass spectroscopists had for the high energy requirement for fragmentation. As the energy of the collisions decreased, an increasing fraction of the collision products were lost due to scattering. The incorrect fragmentation explanation sent the search for higher efficiency in an unfruitful direction and discouraged consideration of a lower energy process.

The second factor was a lack of communication between scientists with different goals. Those studying ion-molecule reactions were familiar with the scattering of their low-energy collision products. But they had no idea it could be analytically useful. Those studying ion fragmentation between sector mass analyzers were focused on the nature of the products and the process of their formation. Having a still different goal, I became a bridge between them.

The distinction between a law and its explanation reveals their separate influences in scientific research and discovery and adds an interesting perspective to those processes.

Exceptions to laws within known limits?

Here we address the final aspect of the second pillar of scientific uncertainty: 'Consistency is no proof of certainty.' An exception to any regularity or uniformity could be found at any time.'

We have seen how it is common for laws to apply inaccurately or not at all under certain conditions. We called these conditions limits on a law's applicability. But are we sure there is no combination of factors within those limits, that could also be exceptions? For most expressions, it would be impossible to test every infinitesimal value of every factor. Even the simple equation for velocity, distance, and time (velocity equals distance divided by time) has not been tested at every combination of velocity, time, and distance and with every object everywhere on earth. Lacking such verification, how can we be sure there isn't some specific combination of those factors for which the equation does not work?

Here is where explanations play another essential role. There is no valid rebuttal to the consistency argument if we consider only the empirical data upon which the proposed regularity relies, *i.e.*, when we don't consider our reason for the phenomenon following that expression. An explanation for the behavior expressed by the law often provides the means to assess whether a peculiar circumstance within the tested range is a rational possibility.

Here is an example. If you hold a book out and let it go, it will surely fall. We're certain this will happen every time. "Unsupported books will fall toward the earth" is an expression of this relationship between its losing support and its downward motion. As expected, there are limits. The book must not be moving with respect to the earth when it is released, and the book must be denser than the surrounding medium (for instance, air).

But within known limits, do we need to test this expression with every book in every location on the planet to be sure of it? No. And that is because of our explanation for the interaction between the book and the earth. We understand that the book and the earth have mass and that masses attract each other. So we can reliably predict that, known limits aside, all unsupported books will fall toward earth.

If a circumstance were discovered where this gravitational attraction was absent, we could conclude that a condition exists in that situation that interferes with or counteracts gravity. In other words, we would have discovered a new limit. We would then have new information on the nature of gravity and a torrent of gravity-defying inventions would ensue.

Another useful example is the Gas Law (for a given amount of gas, the pressure times the volume is proportional to the temperature). The kinetic theory of gases imagines gas molecules as hard spheres moving through space with a velocity that increases with their temperature. The collisions of these molecules with the walls of their container create pressure on the walls.

This picture or model provides a way to make sense of Boyle's Law. It also tells us that an exception (within the gas law's known limits) could only happen if the gas molecules ceased to have velocities, or no longer collided with the walls of their container. On this basis, the need to confirm the Gas Law for every combination of parameters and every kind of gas is precluded.

Karl Popper, for whom the concept of exceptions was a key part of his work, commented on what could happen that would cause currently accepted laws to fail. His answer is:[22]

> It is perfectly possible that the world as we know it, with all its pragmatically relevant regularities, may completely disintegrate in the next second.

This example supports the idea that a verified law will only fail under a new condition. It also suggests that some laws would not fail unless the change was drastic. I agree. I can't think of a condition in which electrons lose their charge, masses do not attract, or CO_2 gas no longer absorbs infrared radiation—which is not also cataclysmic. So, applied within their tested conditions, our laws will work as long as we're around to care about it.

The framework of the thesis advanced here about what science we know for sure is necessarily empirical, but not wholly so because of the critical role of a credible rationale for the empirical evidence. To have knowledge, we need the data from which the relationship was formed *and the reason for it*. To be scientific, the observations must be real, and the explanation must be at least theoretically testable.

It may seem like circular reasoning to use the explanation, which we have already said may be subject to revision, as the means to exclude exceptions within tested limits. But even a disproved explanation will be replaced by another consistent behavior model that will serve equally well. As we go on, we will see that individual expression/explanation combinations are not isolated entities but parts of an interlocking and mutually supporting network of knowledge that makes each of its components more robust.

Are instrumental measurements valid observations?

Since the invention of the telescope, thinkers have raised the question that if there is nothing in science we can be sure of, on what basis can we trust the results produced by scientific instruments? This is understandable because for many people, the way complex technological devices like computers and cell phones work can seem truly mysterious (and sometimes frustrating). Scientists call instrumental results "observations" even though they were not

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[22] K. Popper, in D. Miller, *Popper Selections* (Princeton U. Press, Princeton, 1985) p. 115.

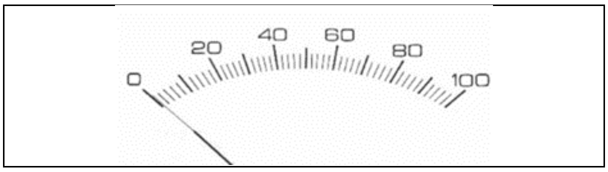
made with our senses. But are they valid "observations"?

To answer that, we must connect the operation of instruments to that which we have determined in earlier sections to be trustworthy. In this section we will see that, broken down, all devices and instruments are just combinations of individual, readily understood, bits whose function is based on verified laws. For a logical argument for why this is so, we will start with some basic measurement concepts.

Instruments designed to measure quantities produce numbers that are related in known ways to the properties to be determined. Unless we can visually count them, there are only a few things we can quantify directly, like the dimensions of an object or the angle between two lines. We compare the length or angle of the object with the numbered marks on a measuring tape or a protractor.

But things like temperature, time, and weight can't be measured with a scale printed on a tape or semicircle. To measure such non-visible quantities, we need devices that will convert the things we want to measure into something we can see. The goal is to produce a number by which we can assess the brightness of a star or the temperature at which a material melts. So, we use a photometer to measure the intensity of the starlight or a thermometer to observe the temperature at which melting occurs.

Here is one way we can measure the intensity of light. A light sensor produces an electrical current related to the photon flux at the sensor. This current moves the pointer in a current meter that has a scale like the one pictured here.



The position of the pointer against the scale gives us a number related to the light intensity. The higher the number, the brighter the light.

The light meter described above employs three conversion devices: a light intensity-to-current converter, a current-to-needle position converter, and our eyes which convert the needle position to a number. Instruments that count things we cannot see like photons, aerosol particles, and red blood cells also require conversion devices. A sensor converts each item or event into an electrical pulse. Another device accumulates the counts and another displays or stores the result.

All electronic measurement devices from those in our automobile dash to those in advanced labs depend on combinations of conversion devices that convert the quantity we want to measure into one that we can see[23].

This principle of measurement has several important consequences concerning the reliability of scientific data. The accuracy and precision of the final measurement depends on the reproducibility and stability of each of the conversion devices and the accuracy of the instrument calibration. Each conversion device in an instrument depends on verified laws that relate its input and output quantities. The assumption that the equations underlying the conversion devices work consistently is valid if the instrument is working within the tested limits of the laws its conversion devices rely on.

For those who argue that we should only believe what we perceive with our senses, I would point out that the sense system in our body uses the same conversion device concept as our instruments. In vision, our photo sensory cells convert photons of light to impulses of charge that our nerves carry to our brain for interpretation. The same is true for sound, taste, smell, and touch. At least in instruments, we know and control how the signals from the sensors are being processed and interpreted. In our bodies and brains, it's more complicated.

The use of instrumentation in scientific measurements is a key example of how science builds on itself. We use valid equations to devise novel conversion devices so we can

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[23] Enke, C. G. *Anal. Chem.* **43**: 69A-80A (1971)

observe new phenomena in reliable ways. For example, adapting a Michelson interferometer to measure gravitational waves.

If scientists who used sophisticated instruments, like computer-controlled telescopes or mass spectrometers, listed all the laws their observations relied on, it could easily run into dozens. When a measurement result challenges accepted models of the system studied, we need to examine all aspects of the instrumentation employed like they did with the OPERA experiment at CERN as described above.

Can an explanation become settled science?

We have shown that there is a part of scientific knowledge that we can be sure of, *i.e.*, the verified laws applied within their tested limits. We have also seen that the explanations of these laws are analogies that may be revised and generally work on only one level of complexity. So one might assume that no explanations are completely settled as representing reality. That could be going too far. There are some explanations that, *at their level*, seem to be final.

The hypothesis of a spherical earth based on the observation of ships disappearing over the horizon would be an early example. There are now so many confirmations of the shape of our planet, including pictures from space, it is no longer vulnerable to reasonable doubt.

When we had competing explanations (geocentric and heliocentric) of planetary motion, neither one was certain. Then, Galileo's observations supported the heliocentric model enhancing its credibility. Since that time, there have been so many incontrovertible observations and confirmations that the conclusion that the earth is among the planets orbiting the sun is no longer in doubt. This is an example of something that began as an explanation but is now 'settled science.' Though we should use the word 'truth' very carefully with respect to scientific knowledge, it does not seem a stretch to say it is true that the planets, including the earth, orbit the sun.

Nor is it questionable that water is composed of hydrogen and oxygen atoms in a ratio of two to one.

The concept of the chemical elements and their masses also began as conjectures to explain various substances and behaviors but have become verified realities. Again, it is important to note that the explanation for chemical composition centered around the elements and interatomic bonds is 'settled' *on the level associated with those entities*. There is still so much to learn about the fundamental nature of matter.

A more recent example is that of the movement of tectonic plates on the earth's surface. Alfred Wegener introduced the concept of continental drift in 1912. This was his most significant scientific contribution, so it may be surprising that his doctorate was in astronomy with strong interests in meteorology and climatology. Perhaps it was a meteorologists' extensive familiarity with maps that sparked his curiosity about how the shapes of the continents, if abutted, fit together so well. From this, and the observation of mid-ocean trenches and ridges, he posited that the continents had drifted to their present dispersion from a contiguous configuration now called Pangea.

But authorities in the field rejected his idea. As the Wikipedia article points out and as we saw in the previous section, "… it didn't help that Wegener was not a geologist." It also did not help that most geologists believed in an idea called isostasy that would prevent continental movement. But evidence of continental drift mounted.

Now called plate tectonics, the concept of continental drift is no longer an explanation for the remarkable picture-puzzle fit of the continental shapes, it is settled science. Geologists have measured the rates of movement in millimeters per year or, more prosaically, at the rate of growth of our fingernails.

It is interesting to consider at what point an explanation becomes settled science. The helical structure of DNA was at one time a conjecture but is now no longer in question. A concept becomes increasingly certain with the accumulation of confirming data. We have learned which nucleic acids make up its base pairs and how they form the overall helical structure. This has been confirmed, initially by X-ray analysis, but more recently by atomic force microscopy. Several variants have been found and been characterized.

As we empirically reveal more details, the initial concept becomes more settled, or as I put it, settled *in fact*. But, until empirically verified in incontrovertible ways, an explanation, no matter how sensible, is provisional.

This empirical confirmation is essential to the firm establishment of an explanation. An explanation can appear to be settled science by its widespread acceptance and repetition. Current examples are the cosmological concepts of dark matter and dark energy. There are many reasons to believe they may exist since their postulation explains the acceleration in the rate of expansion of the universe and resolves observations of stellar velocities inconsistent with the laws of gravity.

Many publications assume that their reality has been established. But *the absence of reasonable alternative explanations is not the same as empirical confirmation*. That's why we are making such efforts to find the source of the "missing' matter and energy. Until then, they are just postulates.

Is the real world too "messy" for scientific laws to work?

In this section, we address the third pillar of scientific uncertainty, which is that our 'simple' laws do not apply in the real world where multiple phenomena can affect the outcome.

The philosopher best known for this argument is Nancy Cartwright[24]. Her point is that measurement results can only be confined to a single cause or phenomenon under carefully controlled conditions (read laboratory). In the real world, even in as simple a case as Newton's law relating force, momentum, and acceleration, other phenomena occur when applied to a vehicle on a street. They include friction with the surface and air resistance to the vehicle's motion. In predicting the trajectory of a falling leaf, air currents and the leaf's orientation affect the outcome.

Cartwright is, of course, correct that observations in the real world are rarely constrained to a single phenomenon. Indeed, it would be hard to find, even in the laboratory, experiments that are free of extraneous influences. Every experimental scientist knows that her measurements have a degree of imprecision. Measurements precise to one part in a million have variations in the seventh decimal place because of uncontrolled variables.

So, exactness in a measurement is virtually always a matter of degree. The critical question then is whether it meets the need of its application. The measurement devices used by carpenters framing a house are less exact than those used by cabinet makers. The pH strips with which one measures the acidity of spa water are crude compared to the pH meters used in biological research. But each meets its need.

Experimental scientists spend a substantial part of their time determining whether their measurement results are exact enough to support the conclusions they deduce from their experiment. Statistical data analysis tools, and the skill in using them are essential parts of scientist's kit and training. The reviews of papers include critiques of data analysis.

That brings us to the question of whether a measurement, which meets the need of its application, is wrong because it is not perfectly exact. From a practical standpoint, it is correct. The same is true from a philosophical point of view. Some observations can be clearly true or false. Jack is wearing a shirt with a buttoned front, or he isn't. But the determination of how long it takes him to put it on involves a numerical measurement which may be accurate to the minute or microsecond. In any case, there will be a limited number of

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[24] Cartwright, Nancy, *How the Laws of Physics Lie*, Oxford University Press, 1983.

places in the result and therefore an uncertainty in the following place. Expecting the number of significant places to be infinite denies the validity of virtually every measurement ever made.

Yes, the world is messy. But is it too messy for scientific measurements to be valid? Our scientific laws make useful predictions consistently. They work because their accuracy and precision are sufficient for the task at hand. The greater the precision the task requires, the more we must control the factors affecting reproducibility.

In the other direction, when the uncontrolled variables are too many or too complex, the accuracy of prediction may be less than desired. We can show when the conditions for cyclones are favorable, but not exactly where they will hit or when. We can assess the general effectiveness of a vaccine, but not predict which people will not be immunized. The political, economic, and social “sciences” are another matter altogether.

We look for better means to assess the uncontrolled variables in situations that constrain the predictive power of our physical and chemical laws. But it is overly harsh to cast doubt on the usefulness of all laws because of those situations in which variations in factors are too many and/or too large for the predictive power we would like to have. In the physical sciences, we know when that is the case. And we shouldn’t forget the vast number of cases where the application of scientific laws forms the basis of our way of life.

But we have found another way to deal with the problem of multiple phenomena significantly affecting an outcome.

Simulating reality in complex situations

In both my areas of research, electrochemistry and mass spectrometry, multiple forces are the norm. In the first, there is the electrical attraction between the electrode and ions in solution, the complex nature of the electric field around the electrode, and the motion of the solution relative to the electrode. In the second case, electrical and magnetic forces with complex distributions affect the trajectory of ions in the instrument. Individually, the forces have predictable effects, but in combination, a single mathematical solution is often impossible.

When I began my scientific career, the only solution was a painstaking trial adjusting the physical parameters of actual electrochemical cells. The general availability of high-speed computing changed all that through a process called simulation.

Here’s how simulation works. A force (generally a field strength) acting on the object of study is calculated for every point in the operating space. The effect of the force on the object can be calculated for every position it occupies. This is done for each known force acting on the object. Then from the object’s starting position, the computer calculates where the object will be in the next small increment of time as a consequence of all the forces. It then does so for the next time increment and so on. The trail of successive positions is the path of the object through the calculated region. Scientists no longer need to seek a single mathematical formula to resolve such problems.

The increments of time between each calculation need to be small so that there is only a miniscule change in each force over the change in position. The smaller and therefore more numerous the steps, the more accurate the result. The computing power required increases with larger spaces, a greater number of steps and objects followed, and the more forces involved.

I resolved the means to focus ions in a new type of mass spectrometer sixteen years ago using the computing power of a laptop[25]. Gary Hieftje’s group built an instrument following the prediction of the simulation and it worked exactly as the simulation predicted[26]. The

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[25] Christie G. Enke* and Gareth S Dobson, Anal. Chem. 79. 8650-8661 (2007)

[26] Alexander W. G. Graham, Steven J Ray, Christie G. Enke, Charles Barinaga, David W.

problem I solved by simulation was modest compared to the many complex systems scientists simulate in virtually every field of investigation.

Simulation has become an essential tool in all areas of science and engineering. Models of everything from water molecules to black holes can be found in scientists' computers around the world. For example, if we can simulate the way a drug and an enzyme interact, other potential drugs can be 'tested,' even hypothetical molecules that have not yet been synthesized. Molecular simulation now complements the more traditional tests for the biological activity of test substances.

The degree to which computer simulations can mimic reality and what it means if they do are legitimate topics for discussion. The process being simulated does not occur in a series of micro steps in the same way straight-line segments do not make a circle, no matter how small the segments. Thus, the results of computer simulations are estimations of reality. Depending on the model and the complexity of the system modeled, they can vary from extremely accurate, to probable, to just one possibility.

Verification of the simulation process comes from repeatedly correct predictions. Just as with the observational variances discussed in the earlier section, the degree of accuracy of simulations can be found and calculation modes adjusted to produce results adequate to the task. When all significant factors are incorporated into the simulation, the remaining influences are uncontrolled variables.

In some simulations, there can be some variation in the forces acting in each step. When you allow for a range of conditions during a simulation and run it multiple times, each outcome is likely to be different. We see this in the prediction of a hurricane's path. Superimposing many repetitions of the simulation produces a range of paths which gives us a general trend, but the exact path becomes increasingly uncertain the farther you get from the starting point. The larger the effect of the variable factors influencing the result, the wider will be the divergence of solutions.

This is how, by mapping the forces in a space and applying simple force equations to objects over small increments of time, we can predict the outcomes in complex systems. The digital computer has made it a practical and commonly used tool. The degree to which the results correspond to the real world requires empirical confirmation.

Conventions in science: essential, but constraining

Scientists express themselves in a variety of ways, including language, mathematical formulas, graphs, and diagrams. Each makes its own contributions to scientists' communications. Since we now understand that scientific knowledge is made up of laws and their explanations, we can look at how each of these components is best expressed.

For a law to have the qualities defined in earlier sections, it must have a form that is unequivocal in its meaning. Einstein's equation relating energy and mass, $e = mc^2$, is a trite example. All the terms and operations are precisely defined. So, equations fit this need. So also do logical expressions if all terms are used exactly or specifically defined.

The expressions of laws I am familiar with include the equations of chemical reactions, mathematical equations, logical equations, electrical circuit diagrams, and diagrams of chemical structures. Such equations and diagrams are essential tools for the scientists, providing exact expressions, and having become conventions, they convey the same meaning to scientists worldwide. But, again, they do not explain themselves.

Explanations rarely share the precision of communication needed for laws. Here English, and I suspect all major literary languages, fails us. To have no confusion between what the speaker intended to express and what the

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Koppenaal, Gary M Hieftje, *J. Am. Soc. Mass Spectrom*. **22**, 110-117 (2011) listener heard, every word should have just one meaning, regardless of the context. You know, from your dictionary, this is rarely the case. We can't even hold on to the original meaning of "unique."

If languages did not have a built-in ambiguity and flexibility, we would have no need of a thesaurus. There would be no metaphorical use of words and no inferences. In short, I fear there would be no poetry and a few exquisitely turned phrases. Isn't it good to have a language that supports, perhaps even promotes, such creativity?

But within the prose of explanations, scientists need to communicate quantities like energy, mass, time, and temperature, both in amount and with a mutual understanding of the quantity being expressed. Science depends heavily on the standards developed for these quantities. In fact, we've agreed on an entire system of units for all technical quantities. It's called the Système International d'Unités or SI. Symbols for these units also appear in most laws.

There are seven fundamental units in the SI; all others are derived from them. An international consortium is tasked with keeping the system current as measurement precision increases. The new standard kilogram is no longer a piece of platinum-iridium alloy, carefully preserved. Mass is now measured by exactly offsetting the mass of an object with a precisely generated electromagnetic force. All scientists use these SI units in their work and publications, so they have become a kind of universal language for quantities. It's immensely helpful that this is so.

What we may not keep in mind, however, is that these units have resulted from our creation of conceptual systems like motion, thermodynamics, chemical bonding, quantum mechanics, nuclear structure, biological heredity, the expanding universe, etc. They provide functional working paradigms that support progress within a field of study. And among fields, there is considerable overlap of common terms, making the whole of scientific knowledge an interdependent framework.

While essential for progress, the requirement that scientists use these quantities and thus stay within the paradigm, can constrain imagination, and limit the form that new knowledge can take.[27]

Science: A product of human creativity and discovery

Scientific findings are usually conveyed to students and the public as disembodied facts. Most presentations lack the story of how that knowledge came about. But for those who produce scientific knowledge, as with artists, their work is a personal creation. Research scientists in every field are aware of who first developed the concepts they now rely on. It has always been this way. Laura Snyder[28] tells us how 18th century natural philosophers coined the term 'scientist' as a parallel to 'artist' thus recognizing its creative aspect.

It is reasonable to think that if the laws of nature we have discovered are true, they would be the same regardless of who revealed them or where or when the work was done. This concept of scientific research is analogous to a treasure hunt where there is creativity in deciding where to look and how to interpret the clues, but the objects to be found are predetermined.

Understanding scientific knowledge as cross-cultural and universal leads to thinking that equations etched into a metallic disc sent out in a space capsule would be recognized by intelligent extraterrestrials. Humans created the concepts of work, entropy, and energy and scores of other quantities. But are most other sentient species likely to have organized their observations of nature in the same way?

Jacob Bronowski doesn't think so:[29]

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[27] Kuhn, Thomas, *The Structure of Scientific Revolutions, 3rd ed*., University of Chicago Press, Chicago, London, 1962.

[28] Snyder, Laura J., *The Philosophical Breakfast Club*, Broadway Books, New York, 2011. *p. 165.*

[29] Bronowski, Jacob, *A Sense of the Future*, *Essays in Natural Philosophy*, MIT Press, Cambridge Massachusetts, 1977.

> Knowledge grows because human minds work at that, and it is a workaday job which we have to get on with; no stroke of luck will find knowledge for us, for it is not there to be stumbled on, ready-made, like a lost corridor. It is not even there to be put together from its parts like a prefabricated building.

Further:

> None of these metaphors describes the reality of scientific knowledge because all of them suppose that there is somewhere a structure of knowledge which is closed. But knowledge is not a structure in this sense at all; it is not a building, or any piece of architecture; you could not put the roof on it or close it with a keystone.

And:

> Our discoveries are creations, not preordained conclusions, and the raw materials that go into that process are likewise not predetermined.

From this point of view, not only is our organization of knowledge specifically human, there is also no consistent pattern in its creation. In my experience, breakthrough realizations have most often come when I was just waking or doing some semi-autonomous thing, like taking a shower. It's as though my mind has been working in "background" mode and is most successful when unimpeded by stress and undirected by effort. I don't know how to trigger such events, so I'm just grateful when they occur.

Carlo Rovelli[30] sees it as having a vision.

> Science begins with vision. Scientific thought is fed by the ability to 'see' things differently than they have previously been seen.

The last part, coming up with an explanation for what is discovered, involves imagination. The word itself is derived from the making of images in the mind, which then, through analogous processes, extends our knowledge.

The stories of scientific intuition and revelation in the history of science are as fascinating as they are varied, which is not surprising since we all are wired differently from the moment of our arrival and then individually shaped by personal experience. Despite the often-monolithic characterization of scientists, we are a remarkably varied lot. The mentors we worked with were significantly disparate in their backgrounds, interests, and methods.

Then there are all the non-technical experiences that factor in, such as being handy with tools, having an interest in gardening, photography, or music. These individual qualities and life stories unavoidably affect how we go about our investigations and where our interests and imagination will take us.

Creating science is making sense out of our observations of natural phenomena. We can only see what our senses (often aided by instruments) tell us. Even among creatures on earth, these vary greatly. Surely the world view of whales is vastly different from our own. The stuff from which we infer our laws is bound by what we can experience. Then, regarding explanations, they can only 'make sense' if they correspond to other behaviors with which we are familiar.

Even though scientific knowledge is the result of a creative process and likely not universal, it works for us, and our lives are, for the most part, the better for it.

Scientific bias

A pleasure and a benefit of doing scientific research is becoming a member of a community of investigators working in the same field. Over years of attendance at professional meetings and reviewing each other's papers and proposals, we form mutually supportive connections. "Membership" in one's group is informal, but the people in it soon catch on to who is 'in' and what they are working on.

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[30] Carlo Rovelli, *Seven Brief Lessons on Physics*, p. 21.

These are the assumed ‘experts’ in the field and innovative ideas are not expected to come from those outside the group. This is especially true of ideas (or even data) that call to question the accepted explanations for the laws they employ.

Earlier, we saw the initial resistance to continental drift, that suggestion coming from someone outside the group. I had the same experience twice in my career. The first was the difficulty in getting funded to build a tandem mass spectrometer for automated chemical analysis. (“It couldn’t work.” “I didn’t know what I was doing.”) The second was the equilibrium partition explanation for selectivity in electrospray ionization.

In the first case, I had no publications in mass spectrometry but was known for innovative electronic instruments, and in the second case, it was my first foray into methods of ionizing samples. The reviews of submissions that were negative were broadside rejections rather than reasoned critiques of the concepts I introduced. My recognitions in related areas helped, and now I am a “member” in both areas.

Besides an in-group’s resistance to challenges of their assumptions, more personal considerations can create bias. In the early 1930s, Enrico Fermi was bombarding various elements with neutrons. The products were routinely atoms with a modest decrease in atomic weight. But with a uranium target, he claimed, from chemical analysis, to have produced a heavier, previously unknown element. In other words, he believed the bombarding neutrons were being incorporated into the uranium nucleus instead of knocking a bit off.

Ida Noddack, a German chemist and physicist, noting Fermi’s analytical method, authored a paper in the 1920s listing the much lighter elements his method could have detected instead. She was the first to suggest a major fragmentation of the nucleus, i.e., nuclear fission. His belief in nuclear stability deterred Fermi from considering this possibility. He received the Nobel Prize for his work on nuclear bombardment. Noddack, nominated four times for her breakthrough suggestion, did not.

This story is reminiscent of Watson and Crick’s use of Rosalind Franklin’s definitive X-ray data in the discovery of the double-helix structure of DNA. Franklin was not aware that her colleague, Maurice Wilkins, had shared her data with Watson. Wilkins shared the Nobel Prize, but not Franklin.

Both these stories conjure up suspicions of gender bias which one would hope has decreased since then. But the *New Scientist*[31] reports that when proposals for access to time on the Hubble space telescope were made anonymous in 2017, the success rate for women-led teams more than doubled, giving them an unprecedented edge over male-led teams.

Of course, gender is not the only basis of bias. Others include ethnicity, language, academic pedigree, and prestige of institution. I believe it is largely unintentional, from having instinctively adopted the outlooks of our peers and mentors. We can only try to be more conscious.

But not everything proposed is worth pursuing. The profound and novel are mingled with the groundless and trivial as they cross reviewer’s and funder’s desks. Despite the perception that scientists are always objective, we make judgement calls like everyone else. There will be some mistaken resistance like nuclear fission and low-energy ion fragmentation, and we will follow some false positives like cold fusion for a while. But we might miss fewer innovations if we didn’t confuse current explanations with truth and if we didn’t dismiss ideas because of who had them.

Outside the box, looking in

We hear a lot about thinking outside the box. Wikipedia defines it as “a metaphor that means to think differently, unconventionally, or from a new perspective.” In the history of science, there have been many examples of discoveries that came about by thinking ‘unconventionally.’

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[31] *New Scientist*, 21 December 2018

One of my favorites is Lavoisier's discovery of oxygen. He was one of several scientists studying the chemistry of combustion around 1775. The prevailing theory was that burning something released a substance. That explained why a piece of coal or wood loses weight and size when burning. The substance released was called "phlogiston."

This explanation made sense, but there was an anomaly. When sulfur or phosphorous burns, weight is gained. Lavoisier considered the possibility that the addition of something during burning was the norm, not the aberration. He reasoned that, with some flammables, the added substance which he called oxygen created a gas which went away. In other cases, the product of combustion was not volatile, and the oxygen remained, making the starting substance heavier.

Other examples of thinking from a new perspective are the above-mentioned Ida Noddack's interpretation of Enrico Fermi's neutron bombardment experiment and Alfred Wegener's postulation of continental drift.

Thinking outside the box is not easy if your professional life has put you in it. When I was trying to design a new kind of mass spectrometer called distance of flight (DOF), getting outside the box of 'standard' mass spectrometry principles was a struggle. I understood time-of-flight mass spectrometry (TOF) in which different substances fly down a tube at different rates and reach the detector at different times. In DOF, I wanted to see the positions each of the substances would have after a given flight time. Imagine 'freezing' a 100-yard dash just before the front runner has crossed the finish line.

Focusing the different substances at their detection point is needed for reasonable resolving power. The method to achieve focus in DOF would differ from TOF, but subconsciously holding on to the 'rules' of TOF focusing kept getting in the way. It took months of studying simulations to learn the characteristics of this new system (and unlearn the old). When I solved the problem, it made sense, but from a completely new perspective.

Resolving situations where new data conflicts with existing explanations can be easier when you are outside the box looking in. You are not as stuck on the shared beliefs of the 'in' group. But then, as we have seen above, the 'insiders' might not welcome your intrusion. Perhaps if, while believing our data, we could hold our explanations more lightly, outside-the-box ideas would be more available.

Astrophysicists may need that at the present time. The James Webb Space Telescope (JWST), which is sensitive to infra-red photons, can see spectral lines that have been redshifted further than were previously observable. Greater redshift means a greater velocity of the light source away from us. Based on the universe expanding at an increasing rate, that also means the sources are at a greater distance and the light has taken longer to reach us. It's that same expansion, played backwards, that gives us the age of the universe, or the time since the big bang (13.8 billion years).

The problem is that the JWST has seen mature galaxies like the Milky Way that are calculated to be only four or five hundred million years old when their light started toward us. We thought it took much longer to form such a galaxy. Our Milky Way galaxy is thought to have begun 13.1 billion years ago and taken several billion years to form. We are at that point where observations are dissonant with current explanations. Either galaxies can form more quickly than we thought, or the universe is more than 13.8 billion years old.

It's time for thinking creatively. But however we resolve this, the data will remain valid, as will the laws governing the spectra of the elements, the measurement of brightness, and many others. It is our explanation of some observations that will adjust. My bet is that a mechanism other than the Doppler effect is contributing to the redshift.

The importance of a story

The book, *Houston, We Have a Narrative*[32], by Randy Olson, subtitled, *Why Science Needs Story*, resonated with me. I needed help telling the story of my experiences in science to a lay audience. Olson contrasts the lifeless formalism of a technical paper with things people read by choice. A relevant story draws us in and keeps our attention.

If a relevant story helps convey a message, why do we scientists work so hard to avoid it in the papers we write for each other? Among the few bits of scientific writing advice I got was to not tell the experimental sequence chronologically. Perhaps that's the reason we avoid a story. But the order of events isn't a story. The story is in the novelty and significance of the work. We could start there. That's what scientific journalists who write about science for *New Scientist* or the *New York Times* do.

But there is another reason that the story and the message go hand-in-hand. Just as scientific knowledge is composed of laws and explanations, I argue that knowledge in general is a combination of facts and the stories we associate with them. When baffled by a person's stubborn attachment to a belief in the face of contrary evidence, we find that it's the associated story the person can't relinquish. *If we want to change people's minds, we must modify or replace the stories associated with their beliefs.* And the only way to do that is with a story that is more compelling.

And speaking of beliefs, I don't think it wise of scientists to suggest we must make an either/or choice between science and spirituality. Science is based on regularities or reproducible phenomena. But one's personal experience of the transcendent is not available for manipulation any more than you can reproduce on demand, the shiver once experienced from a beautiful scene or a musical performance. Scientists who dismiss the experiences of others just because they do not have an explanation for them are guilty of their own version of fundamentalism.

Very few nonscientists get their information about research results from the scientists themselves. Most depend on the organizations, companies, and institutions whose charter is to tell us what is going on. Journalists and reporters covering the scientific world would ideally have as much understanding of how science is done as sports reporters have about the nuances of the game on the field and in the locker room.

This is often not the case, which leaves us with comments on scientific conclusions or technological advances without a back story. What science went on behind the latest drug development? Where was it done? Who was on the team that discovered/created it? What stimulated the creative breakthrough? How was it tested? I have a special eyeroll for the phrase "Scientists say…" But as we have said, bolstering scientific fact is not enough to change belief.

We have gathered our beliefs through stories shared among the groups of which we are members. People have an explanation, plausible to them, for the beliefs they cling to. For instance, "The earth has gone through cataclysmic climate changes since prehistoric times. Human activities did not cause them then and are too insignificant to cause them now."

In our public media, there is a lot of on-screen debate. Competing opinions are easy to find, but the more interesting and informative stories are those behind the science. The story of the advent and evolution of the science of glaciology, as told so well in John Gertner's[33] *Ice at the End of the World,* beautifully lays out the bases for its conclusions. It's impossible to read this book without feeling alarm at the ice melt in Greenland and Antarctica and its relationship to the burning of fossil fuels.

In most areas of creativity, the products of inspiration are identified with the person who created them. It was sometimes that way for scientists, too. We have Newton's Laws of Motion, Darwin's Theory of Evolution,

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[32] Olsen, Randy, *Houston, We Have a Narrative: Why Science Needs Story*, University of Chicago Press, Chicago, 2015.

[33] Gertner, Jon, *The Ice at the End of the World,* Random House, 2019.

Maxwell's Theorems of Electromagnetism, and so on. Personal attribution of a scientific breakthrough is now rarer.

Why aren't names of the inventors of integrated circuits that have made modern computers and all "smart" gadgets possible part of our vocabulary? (Jack Kilby and Robert Noyce). Could we say who developed the method CRISPR by which we can edit genes? (Jennifer Doudna and Emmanuelle Charpentier). These are culture-changing advances whose attributions are not at the tips of most tongues.

There are standouts we can name and picture in many areas of endeavor. But who are the contemporary scientists we look up to? Our scientist stars are rarely publicly celebrated. It isn't because there are too few worthy of appreciation. There are dozens, scores, hundreds of individuals who are successfully prying open nature's secrets, creating new tools, and making our lives more secure and comfortable. If not heroes, they are at least great role models. Let's tell their stories, too.

Summary and conclusions

Here are summaries of the principal epistemological points of the earlier sections.

- *Theories have two distinct parts: laws and explanations.* They are the "what" and the "why" of our knowledge. The laws, based on observations, do the quantitative and logical work, but they do not reveal why. That is the task of explanations which are our rationalizations, models, and pictures of why this is so. Their qualities and contributions to scientific knowledge are distinctly different, but equally essential.

- *Laws can be certainties, but not universalities.* They have proved to work consistently within the limits of the conditions in which they have been tested. Applications beyond those limits are assumptions and associated conclusions are therefore provisional.

- *Limits to a law's certain applicability are those conditions which haven't been verified or they are conditions under which other related phenomena affect the result.* Most laws have limits on the range of conditions within which they accurately apply.

- *Exceptions to a law's applicability are limits on its application: they are not disqualifications.* Having verified the certainty of a law within its limits, exceptions must occur under conditions outside those limits.

- *Catastrophic changes in conditions have only philosophical significance.* Karl Popper names the disintegration of the world as a situation in which current scientific knowledge would fail to apply. Other situations would include our planet's being swallowed by the expanding sun. While these are philosophically valid exceptions, in practical terms, there would be no one left to care (or gloat). In the meantime, the laws will continue to work within their verified limits.

- *Instrumental measurements are valid observations*. Instruments of science are based on verified laws, which give certainty to their results when used correctly and within limits. Errors in their application show up in attempts to confirm or verify reported results.

- *The influence of unconsidered factors in the application of laws are determinable.* Limits of measurement precision due to uncontrolled variables do not invalidate laws or make them "partially true." Determining the variance in observations is integral to science and the results are valid if the precision is adequate to meet the needs of the application. Many situations with multiple significant phenomena having known laws are resolved through computer simulation. The existence of situations where the uncontrolled variables are too large is a sign that the science is incomplete. We need ways to take the other contributing factors into account.

- *Explanations are the way, based on our experience, we make sense of natural phenomena*. They are necessary and useful, but they are models or analogies, not truths. Without a testable explanation, human creativity–making the stories of its development and its success very much worth telling a theory is unscientific conjecture.

- *Different explanations apply at various levels of complexity*. No single explanation applies at all levels. The deeper we go into the phenomenon, eventually to the fundamental nature of matter and energy, the more elusive analogies to things we understand or experience become.

- *Multiple explanations of a phenomenon can be simultaneously useful*. Because explanations are useful analogies and metaphors, there can be more than one way to look at a phenomenon. Each can be more or less useful depending on the circumstances. There is no need to choose.

- *The hallmark of scientific knowledge is that it is empirical*. Laws are generalizations of observations of phenomena. To be scientific, the explanations we conceive for the phenomena must be at least theoretically testable (by observation).

The consequences of the above understanding of scientific knowledge include:

- Conclusions based on laws that are applied within their tested limits are trustworthy bases for policy decisions.
- The concern over the 'truth' of theories (which in this context means explanations) is resolved by realizing that an analogy is not the reality. Explanations help us picture the process and relate it to other things we 'understand'. Their value is not in their 'truth' but in their usefulness.
- Holding explanations more lightly and accepting that multiple explanations might be useful could promote imagining alternative rationalizations of the data. It could also dissuade scientists and writers from assuming an explanation is settled science before it has been empirically confirmed or hanging on to a favored explanation in the face of contrary observations.
- The problem of distinguishing science from pseudo-science or non-science is resolved by science's requirement of empirical confirmation—the data from which the laws are formulated. Hypotheses that are not at least potentially testable are not scientific.

This essay argues that laws proven to work within given limits are certain within those limits; our confidence in them is justified. And while the explanations for the laws are likely to change as science develops, the prevailing ones are essential for understanding and advancing our knowledge of natural processes. Science, useful as it is, and as formalized as it can be, is the product of human creativity; it is not something just stamped by the world on a scientist's mind. This means that making the stories of its development, and its success, very much worth telling, especially for education.

Postscript: Naming this philosophical position

It is worthwhile to put the above view of scientific knowledge into the framework of past and current philosophy. Thinkers as far back as Poincaré, and beyond, have made a distinction between laws and explanations. But they are not always treated independently in science or philosophy, particularly as the word 'theory' is used for either the combination or just for the explanation.

I am a philosophical realist. The physicist/philosopher Mario Bunge has coined the term *scientific realism* which, as he puts it, assumes the independent and prior existence of nature, shuns fictions, theories without empirical support, and measurements without theories and indicators[34]. In other words, nature is real and does what it does, our formalization of its behavior is based on observation, and our explanations must be rational and testable.

I add the caveat that we are only sure that our laws represent reality when they are applied within previously verified conditions. So, I suggest *confirmed scientific realism* as a name for this view. The laws we can trust have been empirically confirmed within their tested

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[34] Bunge, Mario, *Between Two Worlds; Memoires of a Philosopher-Scientist*, Springer International, 2016; *Doing Science in the Light of Philosophy*, World Scientific, 2017. And contributions to Matthews, M.R. (ed.) *Mario Bunge: A Centenary Festschrift*, Springer, 2019.

limits; this confirmation is then supported by plausible, hence rational, explanations.

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