Paradigms Lost and Paradigms Found: Examples of Science Extraordinary and Science Pathological—And How To Tell the Difference**

Nicholas J. Turro*

Scientific Knowledge: Paradigms and Pathologies

One of the most interesting challenges a practicing scientist faces is explaining to a nonscientist how science works and why scientists appear to have a way of knowing that, while not perfect, their discoveries seem to be the best that the human mind has been able to come up with. Scientists, in general, understand the tentative nature of the scientific process and that all conclusions are provisional, at least in principle. Nevertheless, in their everyday activities, scientists often behave as if they are dealing with a set of "truths". This behavior is supported by the manner in which science confidently produces a seemingly unending series of stunning predictions and verifications, which often move rapidly into important technological applications, making the explanatory challenge more difficult. How can one be so sure about what one "knows" and, at the same time, avoid the arrogance of a know-it-all and the pitfalls of intellectual hubris?

In this context, another challenge is to explain how science handles extraordinary claims. How can a scientist tell whether a remarkable idea or experimental observation would lead to the Nobel Prize, which is awarded for science that changes the way that scientists think and know—or would lead to the IgNobel Prize, awarded to pathological science that epitomizes the way the scientific process should *not* work?

Throughout the history of science, the distinction between *revolutionary* science and *pathological* science has not always been so clear. What is the objective scientific process by which one distinguishes genius from nonsense? Both extremes of the scientific spectrum are characterized by a common trait: The ability of the scientist (or a community of scientists) to "think outside the box". But what is this box of which they must be outside? I would identify it as the paradigm, the concept popularized by Thomas Kuhn in *The Nature of Scientific Revolutions*.[1] Science makes quantum jumps when a paradigm shifts but an intricate and complex process with both scientific and sociological components is required to confirm that an extraordinary claim is revolutionary—the content of true paradigm shifts–and separate it from those that are eventually shown to be pathological, destined for the dustbin of scientific history.

For example, during the past century Max Planck published some mathematical computations intended to describe an apparent anomaly in the classical theory of light, which, at the time, was believed to be an unshakable paradigm. The anomaly was termed the "ultraviolet catastrophe", which gives some idea of how severely the anomaly disturbed the scientific community! Planck made the extraordinary suggestion that if light were "quantized" and consisted of bits of energy rather than a continuum of energy, which was the paradigm of the classical theory of light, the anomaly would disappear. At the time (and to some still) this appeared to be a preposterous suggestion, contrary to all known experience and a threat to the reigning paradigm of the classical theory of light. Yet a few years after the paper was published, Einstein connected Planck's suggestion to another anomaly involving the way that light causes electrons to be ejected from a metal (the basis of the photoelectric effect, which operates the "electric eye" of security doors everywhere). The interpretation of the photoelectric effect in quantum terms led to Einstein's Nobel Prize in 1921. For the next several decades the physics community endured a battle royal, with the ideas of quantum mechanics emerging triumphant, if still resistant to explanation in terms of ordinary experience. The emergence of the paradigm of quantum chemistry warns and teaches us that, no matter how bizarre a scientific claim may be or how remote from ordinary experience, it can still be accepted and used by the scientific community and even rapidly applied to technological uses!

But what of the many remarkable claims that have been proposed, debated, and then dismissed by the scientific community as pathological? How was each decision made and how do we know the decision was correct? Are there any rules scientists can follow to minimize the probability of falling into the trap of promoting pathological science?

Mechanisms of Delusion

Troubled science takes many forms, from pseudoscience (irrational or mystical systems of thought dressed up in

[*] N. J. Turro
Department of Chemistry
and Department of Chemical Engineering
Columbia University
3000 Broadway, Mail Code 3119
New York, NY 10027 (USA)
Fax: (+1) 212-932-1289
E-mail: turro@chem.columbia.edu

[**] The author thanks Bill Millard, editor of Columbia University's 21C magazine, for his excellent assistance and collaboration. The support of the NSF (Grant CHE98-12676) is gratefully acknowledged.

  0570-0833/00/3913-2255 $ 17.50+.50/0

ostensibly scientific jargon; often complex but never rigorous) to junk science (methodologically sloppy research usually conducted to advance some extrascientific agenda or to prevail in litigation) to outright fraud. This paper is not concerned with science that results from dishonest practices (which are rarely intellectually interesting) but, instead, with serious investigations leading down pathways that ultimately prove to be erroneous and which may be classified as *pathological science*.[2] As Nobel prize winning chemist Irving Langmuir said in his famous General Electric lecture on the topic, "These are cases where there is no dishonesty involved, but where people are tricked into false results by the lack of understanding about what human beings can do to themselves in the way of being led astray by subjective effects, wishful thinking, or threshold interactions."[3]

The road to greater scientific truth is not just littered with history's errors; it is constructed through a process of constant error correction. If we accept Kuhn's description of scientific progress as a succession of revolutions, or paradigm shifts, resulting from the constant effort to reconcile new results with dominant paradigms, then a scientific field's moments of crisis—when different factions contend over whether an idea or experimental result will turn out to be revolutionary or absurd—tells us a great deal about how knowledge is constructed, tested, defended, and accepted. For this reason, an understanding of pathological science can help a researcher better understand, and perform, reliable science.

Kuhn[1] posits that in the conduct of normal everyday science, researchers sometimes obtain anomalous results; the scrupulous scientist investigates these oddities through experiments intended to disprove the anomalies and reinforce the current reigning paradigm. (We can call this pattern of paradigm-guided scrutiny the First Law of "Parodynamics".) However, if important anomalies persist and resist the best efforts of the community to remove them, a period of intense debate and experimental work results, typically with one community impeaching the correctness of the paradigm and another defending it. A key result may suddenly emerge, supporting the paradigm and revealing the challenging anomaly as pathological; on rare and treasured occasions, a key result convincingly supports a significant revision or "shift" of the paradigm. (Nobel Prizes occasionally follow).

Whatever paradigm may govern a scientific disciple at any given time, it helps to frame and organize a researcher's thinking, acting as a kind of "road map" for inquiries within the specialty and as a safeguard against pathological work. When a science is in a potentially revolutionary phase, a dominant paradigm can be a prison, preventing researchers from following promising new leads, but more often it is a form of conceptual authority, something not to be abandoned without peril. Science often turns pathological when investigators venture outside their familiar paradigm without becoming sufficiently versed in the paradigms of the new field. An informative example[4] is the "cold fusion" controversy of 1989, in which a claim of an extraordinary nuclear process was made, based on some "anomalous" heat measurements made during electrochemical reactions. The investigators, trained as electrochemists, claimed that the nuclear-reaction interpretation was supported by measurements of neutron and gamma-ray emission. However, the latter claims were shown by experts in nuclear physics to be artifacts. The electrochemists could probably have saved themselves quite a bit of opprobrium if they had been better versed in the paradigms of high-energy physicists dealing with the detecting a flux of neutrons or gamma rays in their apparatus.

Since only a few anomalies ever lead to revolutionary change—while most working scientists dream of making exactly that type of discovery of which prestige is made—there is an understandable temptation to interpret unexpected results that can be interpreted as extraordinary as meaningful anomalies. For each community, there is an intuitive evaluation and quantification of an idea's newness, its intellectual potential (in a sense, akin to potential energy in measuring the idea's distance from what an existing paradigm would predict) which might be termed the *surprisal* of the idea or result. A high surprisal implies that the idea or result is well outside of the paradigm. Because high surprisal investigations are both high gain and high risk, the need for the counterpoise of skepticism among investigators studying such topics is acute.

The history of scientific misfires indicates certain patterns, as shown in Figure 1, which I have adapted from a previous publication in this Journal.[5] When a field is in the critical prerevolutionary/prepathological phase, a principle that I will call the Second Law of "Parodynamics" comes into effect: The more drastic the departure from an established paradigm, the greater the chance of either a revolutionary or a pathological outcome—and the more urgent the need for awareness of the mechanisms whereby cognitive errors tend to arise. Figure 1 shows the Second Law of "Parodynamics" for a mature scientific paradigm in action. Everyday, "normal science" follows the uneventful loops in which puzzles endorsed by the paradigm are solved and the paradigm is constantly reinforced.

Figure 1 shows the area of "normal science", consisting of generating puzzles based on the conventional paradigms, solving the puzzles, and thereby reinforcing the paradigms.

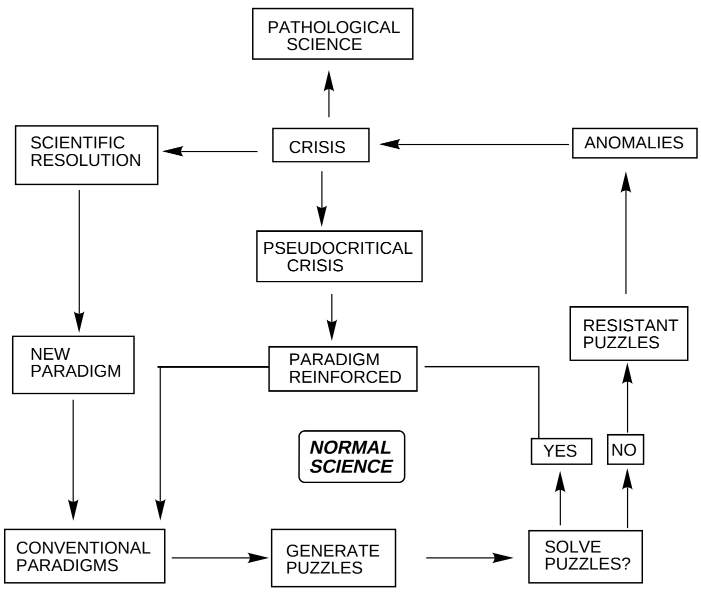

Figure 1. The procedural loops through which science flows.

  0570-0833/00/3913-2256 $ 17.50+.50/0 *Angew. Chem. Int. Ed.* **2000**, *39*, No. 13

From time to time, some puzzles become resistant and, if they remain stubbornly resistant even to the best practitioners in the field, may be considered as anomalies by the community. Anomalous results, unexplainable within a field's governing paradigm and important enough to cause true intellectual alarm within the community, can throw the field into crisis—an unpredictable state analogous to a "catastrophe point" in topological mathematics—which might eventuate in reinforcement of the current paradigm, whether the example is of revolutionary science or of pathological science.

Typically, resolution from the crisis point can take one of three forms: 1) The anomaly's revolutionary potential may be revealed as more apparent than real and this "pseudocritical" state resolves to reinforce the original paradigm in the same way as normal science although with more force because of the excursion; 2) The anomaly may foster a true Kuhnian revolution, resulting in a new paradigm; 3) The anomaly may prove pathological, in which case only zealots continue to pursue it, and the conventional paradigm structure is not only untouched but reconfirmed.

From the Possible to the Plausible to the Probable to the Proven

One way confusion can enter a scientist's thinking involves disruption of the natural conceptual progression through four categories of scientific "cognition". For convenience, we can refer to these as the four Ps:

- The *possible* comprises all ideas that do not violate the most basic and global principles of science (for example, the second law of thermodynamics; the conservation of momentum and energy).
- The *plausible* describes ideas that do not violate the possible and which might be tenable if we could envision circumstances under which they could be realized and tested. (In the celebrated case[6] of "polywater" or polymerized H_2O molecules, there was no a priori reason why a chemical reaction yielding such a substance could not occur and move downhill in potential energy as any reaction must; the idea may be considered as implausible but not impossible, since it only requires that a state of polymerized water exists and is more stable than ordinary water under some conditions.)
- The *probable* describes ideas in "normal or everyday science" as Kuhn used the term: The ideas and explorations that apply an established paradigm and which may extend the scope of the paradigm but do not threaten to overturn or shift it. These ideas are so embedded in the community that they are usually not debated but taken as dogma.
- The *proven* applies to unsurprising exercises in puzzle solving, the routine application of testing or "proving" ideas experimentally, working firmly within a stable paradigm.

The borders separating these cognition levels—particularly between the first two—are not as clear in practice as in theory, especially when a result is of interest to two or more distinct specialties possessing different paradigms. A high surprisal hypothesis may appear impossible from one vantage point, while a different field's paradigm makes it clear that the hypothesis is well within the realm of the possible and merely stretches the limits of plausibility or probability. For example, the low temperature "cold fusing" of two deuterium nuclei or the polymerization of water are currently outside of the paradigm of conventional chemistry and might therefore be termed "impossible" if one is constrained to "ordinary" chemical conditions. In fact, it would be more accurate to term them as "implausible" under extraordinary chemical conditions, such as those of high energy physics. Indeed, the cold fusion experiment did not represent an impossibility, since it is known that nuclei can be fused with the release of enormous energy. The cold fusion experiment represented a "catalyzed" fusion that did not require the high energy physics approach. As implausible as it may seem, the history of science has indicated that clever scientists can figure out how to make "implausible" science occur as long as it is "possible".

Only after an idea has run the scientific community's gauntlet—surviving rigorous experimental and interpretive efforts to falsify it—can it be said to move from a question of possibility to a probable or proven status. Pathological science occurs when an investigator cuts this process short, prematurely trading scrutiny for advocacy.

Sometimes There's No "There" There

Langmuir's classic symptoms of pathological science (Table 1) attribute many errors to various forms of subjective judgment. Uncertainty is part of all science and subjective judgments are inescapable in most fields but statistically marginal phenomena on the threshold of human perception, with a low signal-to-noise ratio, are easy to misinterpret. (Langmuir himself detected this phenomenon in the Columbia laboratory of Professors Bergen Davis and Arthur Barnes in 1930; these physicists believed they were detecting a phenomenon called "electron capture" by alpha particles in a magnetic field but Langmuir found that in their six-hour marathon sessions counting scintillations on a screen in a darkened room they also counted visual hallucinations, which are common in such circumstances, and dismissed observations that conflicted with their paradigm.)

Table 1. Langmuir's[3] six recurring patterns in cases of pathological science

- The maximum effect that is observed is produced by a causative agent of barely detectable intensity and the magnitude of the effect is substantially independent of the intensity of the cause
- The effect is of a magnitude that remains close to the limit of detectability or many measurements are necessary because of the very low statistical significance of the results
- There are claims of great accuracy
- Fantastic theories contrary to experience are suggested
- Criticisms are met by ad hoc excuses thought up on the spur of the moment
- The ratio of supporters to critics rises up to somewhere near 50 percent and then falls gradually to oblivion

To these we may add the following:

- The remarkable result is specific for a "special" system
- Some special technique or equipment is involved
- The result requires a stunning departure from the paradigms that fully determine results in all other comparable systems, including those studied by the authors

  0570-0833/00/3913-2257 $ 17.50+.50/0

Scientists commonly select and discard some of their scattered data points because of suspected confounding conditions or experimental error; in some contexts this may border on cheating but more often it is simply a reasonable and acceptable selection process. In all fields, the requirement of reproducibility within statistical limits guards against this kind of observer error.

The red flag of pathology should thus appear any time a researcher offers resistance to the challenge of reproducibility, claiming that only a certain special system (or even certain investigators) can generate the anomalous result. Such an example may be found in the notorious case[7] of "infinite dilution" studies, which held that antibody solutions remained biologically effective even when diluted so thoroughly that no molecules of the solute were detectable in the fluid, implying that water somehow retains a memory of molecules that have been dissolved in it. If confirmed, this hypothesis—highly implausible but not impossible according to chemical paradigms—would have overthrown some of chemistry's fundamental beliefs about the properties of water; independent investigators found that the investigators reporting infinite dilution did not apply proper controls for observer bias or sample contamination, excluded conflicting measurements, "massaged" the statistics, and neglected to investigate reasons for failures of reproducibility. Rather than acknowledge that his group had been pursuing a pathological inquiry, the leader of the laboratory has clung to his theory, and acquired not just one, but two, IgNobel prizes for improbable research. The course of the infinite dilution story matches Langmuir's symptoms smoothly.[2, 3]

Interpreting Something into Existence

Not all scientific pathologies, however, are covered by Langmuir's list. Another instance of pathological science, the debate over polywater[6] in the 1960s, illustrates a common type of shortcut: a failure to consider standard alternate hypotheses with a paradigm to explain an apparently extraordinary result. Deryagin and other researchers were able to produce a dense liquid, through condensation of water in tiny capillaries, that was claimed to be a new, polymerized form of water, polywater. It should be noted the observations made by Deryagin could be made reproducibly and with exhaustive attention to controlling physicochemical variables and answering colleagues' critiques. Nevertheless, the dense liquid ultimately turned out to be an artifact caused by impurities in ordinary water. Deryagin and a worldwide network of adherents to his theory pursued the polywater concept to extraordinary lengths, in part because of plausible theories about the behavior of water molecules in ultrafine capillaries (and probably in part because of heavy funding from the U.S. Navy,[8] which took an interest in possible military applications of polywater!). However, when purification tests using more sophisticated equipment convinced Deryagin to reconsider an obvious hypothesis he had previously rejected—that the dense liquid was not polywater but simply water that was contaminated somehow—he readily and honestly conceded that his original experiments were flawed, invalidating any interpretations based on these results.

The scientific process healed itself in this case, though not as quickly as it would have if Deryagin and others had kept Occam's razor in mind and given more weight to the simplest available explanation, contamination. A favored hypothesis can develop its own momentum, especially when a researcher invests his or her prestige or professional self-identification in one idea to the exclusion of competing (and often more parsimonious) explanations for the results. Having formed a pet conclusion, the scientist often defends it using its own terms, models, and assumptions. Assuming one's conclusion, rather than challenging the hypothesis before accepting a conclusion, the scientist introduces logical circularity into the interpretation of results. Such pathologies, although not in Langmuir's list, certainly are of the same ilk, as they refer to "what human beings can do to themselves in the way of being led astray by…wishful thinking."[3]

A sensational result can also be inextricably confused with a sensational interpretation. Pathological science often involves a relatively sensational interpretation of an unexceptional observation; the cold fusion episode offers an instructive example. The actual experiment involved an anomalous temperature rise during electrolysis. The translation of this observation led to the conclusion that the "only" source was a nuclear process. The observation of an atomic explosion dwarfs any interpretation of the causal relations and scientific principles leading to it and, on some level, the cold fusion investigators may have been comparing the energy-generating potential of cold fusion to that of the H-bomb. Lacking a spectacular observation, they generated all the media "bang" they needed through their interpretation.

It is interesting that the pathological stories of cold fusion, polywater, and infinite dilution, all involve properties of water and provide shining (or perhaps glaring) examples of how implausible ideas can run amok. Perhaps it is because water is essential to life, has numerous properties that are indeed anomalous (or at least ill understood), and is rich in metaphoric connotations, that it seems to bring out the nonskeptical enthusiast in some researchers.

Surrounding all the common shortcuts around established scientific methods are the human flaws that imperil any kind of enterprise. Extrascientific considerations such as media attention, professional standing, promises of monetary gain, ideological predilections, hubris Nobelicus, and pressures from interested parties outside the scientific community can all contribute to and encourage self delusion. The exigencies of funding may tempt even the most scrupulous basic researcher to hype or overstate practical benefits when describing new work to potential supporters. Today's academic environment—which can appear more like a media fishbowl than an ivory tower—also presents the scientist with ample channels to speak to the general public with a considerable risk of misrepresenting the content, purpose, and potential of a scientific discovery, either in an effort to simplify professional jargon (the ever present problem of "dumbing it down") or in the highly contagious enthusiasm over an untested idea or potentially extraordinary but preliminary observation. These are not paradigm questions, of course, just questions of objectivity and professionalism.

  0570-0833/00/3913-2258 $ 17.50+.50/0 *Angew. Chem. Int. Ed.* **2000**, *39*, No. 13

Advice for the Working Scientific Revolutionist

Clearly, scientific progress would be impossible if researchers always played it safe within a dominant paradigm, discarding disturbing results, or shying away from daring hypotheses. Some of today's most robust discoveries and most promising research subjects—manned space flight, wave–particle duality, C_{60} (buckminsterfullerene, buckyball) molecules, high temperature superconductivity, and so forth—once struck mainstream scientific opinion as sheer fantasy. Perhaps there are some practical steps that a working researcher can take to lower the chances that today's "eureka!" will be tomorrow's IgNobel:

- Always generate and test several plausible hypotheses to explain experimental results.[9]
- Let the best available paradigm be your guide until you are certain that your results require revision of the paradigm.
- Be conservative about the concepts of statistical significance and margin of error, especially when analyzing phenomena on the threshold between signal and noise and particularly when the results appear to be extraordinary.
- Reproduce, reproduce, reproduce.
- Capture the phenomena by two or more truly independent methods. If the results are consistent by two or more independent methods, you have paid due diligence and earned the right to claim that your observation is real.
- Discuss surprising findings openly with peers (through both formal and informal channels, inside and outside one's own specialty) and make constructive use of the critiques that arise.
- When discussing research with nonscientists—especially those holding microphones, cameras, notebooks, or checkbooks—avoid the temptations to overinterpret results, oversimplify your explanations, or promise direct practical applications.
- If further studies convincingly falsify your hypothesis, and you are convinced also, acknowledge it. Blind leads are nothing to be ashamed of; they are inseparable from the progress of science. After any number of pathological investigations, there is eventually one like quantum mechanics, which necessitated a few adjustments to the law of conservation of mass but ultimately withstood criticism, explained results that Newtonian theory couldn't explain, and revolutionized physics. The same communal corrective processes that falsified one theory verified the other; that is how science operates and why it almost always works.
- Do the unthinkable! Try your very best to find faults in your experiment and to falsify your interpretation in a serious fashion. We should recognize[9] that once a scientist devises an original and satisfactory explanation for an apparently extraordinary phenomenon, from "that moment, affection for one's intellectual child springs into existence, and as the explanation grows into a definite theory one's parental affections cluster about the offspring and it grows more and more dear to the individual…[t]here springs up also unwittingly a pressing of the theory to make it fit the facts and a pressing of the facts to make them fit the theory." The more extraordinary the result, the more the principle investigator should try to destroy their claim by running critical experiments. One must be willing to kill one's own intellectual offspring! After all, if one's "apparently" extraordinary science is correct, one will not be able to destroy it. The best way to separate revolutionary science from pathological science is to be brutal and let the battlefield of ideas and experiment decide the victor. Even if you do turn out to be wrong, you will have been true to your science and will be admired by the community for your intellectual courage and dedication to the scientific ethos.

Conclusions

Kuhn's paradigms[1] and Langmuir's symptoms of pathological science[2, 3], provide the scientist with valuable intellectual tools to avoid pitfalls in the scientific process. The paradigm is conservative and *discourages* revolutionary science. Effectively, the paradigm of a discipline is the sociological, scientific, and intellectual structure that serves as a barrier to caution the community about accepting revolutionary claims. Pathological science, on the other hand, is quick to accept the extraordinary interpretation and rationalize the conservative interpretation that falls within the reigning paradigms. Every scientist has probably felt the tension between paradigmatic and pathological science, between the ordinary, normal result and the extraordinary, amazing result. The author hopes that this essay may be useful as a guide for chemists to recognize and differentiate science extraordinary from science pathological.

[1] T. S. Kuhn, *The Structure of Scientific Revolutions*, 2nd ed., University of Chicago, Chicago, **1970**.

[2] Case studies in pathological science: D. L. Rousseau, *Am. Sci.* **1992**, *80*, 54–63.

[3] Pathological science: I. Langmuir, *Phys. Today* **1989**, *42*, 36–48.

[4] a) F. E. Close, *Too Hot to Handle. The Story of the Race for Cold Fusion*, W. H. Allen, London, **1990**; b) E. F. Mallove, *Fire from Ice: Searching for the Truth Behind the Cold Fusion Furor*, Wiley, New York, **1989**.

[5] "Geometric and topological thinking in organic chemistry": N. J. Turro, *Angew. Chem.* **1986**, *98*, 872–892; *Angew. Chem. Int. Ed. Engl.* **1986**, *25*, 882–901.

[6] Polywater: F. Franks, *MIT Press Energy Lab. Ser.* **1981**.

[7] "High-dilution experiments a delusion": J. Maddox, J. Randi, W. W. Stewart, *Nature* **1988**, *334*, 287–290; Dr. Jacques Benveniste replies: J. Benveniste, *Nature* **1988**, *334*, 291.

[8] Dr. Brian Pethica, currently adjunct senior research scientist at the Henry Krumb School of Mines (Columbia University, NY), was one of the principal Western investigators of polywater while heading the Unilever Research Laboratory near Liverpool (UK) and predicted at the time that chemists "would see polywater papers until the Navy's $4 million runs out."

[9] J. R. Platt, *Science* **1964**, *146*, 347–352.

  0570-0833/00/3913-2259 $ 17.50+.50/0