Uncertain Science . . .
Uncertain World

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1 Setting the stage

This is a book about uncertainty, particularly the uncertainty we associate with science. Over the years, scientific uncertainty has been addressed by natural scientists, engineers, medical researchers, social scientists, and philosophers. But for all the perspectives that have been laid out in everything from short essays to scholarly monographs, the richness of scientific uncertainty has often been unappreciated and/or misunderstood by the general public, people not regularly engaged in science.

Uncertainty, of course, is not confined to the world of science. It is an everyday fact of ordinary life as well. We regularly face uncertainty in a myriad of ways. Will it rain today? Will Aunt Dorothy's plane arrive on time? Will the stock market tumble? Will an accident snarl the freeway during rush hour? These day-to-day uncertainties come and go, and we move on through life, sometimes preparing for them, but more often just plowing through them.

But uncertainty also colors longer-term concerns. Will my pension program be sufficient two decades from now to enable the full and comfortable life that my wife and I hope for? Will our health allow a free and independent life-style thirty years in the future? These longer-term questions are harder to answer and are cloaked in greater uncertainty. Because we have only one life to live we cannot return to 'Go' and take another path. Of necessity, we must plan, make decisions, and do our best, all the while evaluating our actions and making mid-course corrections according to our best judgment at the time.

Uncertainty is hardly confined to the future alone; it characterizes our knowledge of the past as well. Adopted children wonder about their birth-parentage, families have difficulty reconstructing the circumstances that led great-grandparents to emigrate. Military historians continue to reconstruct various scenarios for General Gordon's last days in Khartoum, or for Major Custer's last stand in the hills overlooking the Little Bighorn. Geologists are far from settled about the causes of ice ages, and paleontologists still debate the evolution of birds. Our understanding of the past is uncertain because the record of the past is incomplete and to some degree inaccurate. Often the evidence that we do have appears contradictory.

Throughout life, people are immersed in uncertainty. They routinely accommodate the uncertainty with a variety of rational, accepting and non-hostile responses. At a simple level, an urbanite might carry an umbrella to meet the possibility of rain; at a more complex level, a farmer might participate in a commodity futures market to protect against the possibility of a drought. Retirement fund managers routinely make investment decisions in the face of considerable long-term economic and political uncertainty, and home and car owners purchase insurance to protect against catastrophe in an unpredictable future. These are all rational actions taken in the face of uncertainty. Nevertheless, there is sometimes a reluctance on the part of decision-makers to take actions addressing complex science-based issues in the face of similar levels of uncertainty, in part because they feel inadequately prepared to contextualize and evaluate the attendant scientific uncertainty. The topic of global climate change illustrates both the scientific complexities and uncertainties, and the difficulties that people and nations have in formulating rational policy addressing the many facets of a changing climate on Earth.

Several themes will run through the chapters of this book, which more or less define my perspectives on accommodating uncertainty, whether ordinary or scientific:

- Uncertainty is always with us and can never be fully eliminated from our lives, either individually or collectively as a society. Our understanding of the past and our anticipation of the future will always be obscured by uncertainty.

- Because uncertainty never disappears, decisions about the future, big and small, must always be made in the absence of certainty. Waiting until uncertainty is eliminated before making decisions is an implicit endorsement of the *status quo*, and often an excuse for maintaining it.
- Predicting the long-term future is a perilous business, and seldom do the predictions fall very close to reality. As the future unfolds, 'mid-course corrections' can be made that take into account new information and new developments.
- Uncertainty, far from being a barrier to progress, is actually a strong stimulus for, and an important ingredient of, creativity.

THE GARDEN OF UNCERTAINTY

Throughout this book, you will be taken on some scientific excursions that will illustrate how uncertainty is woven into the fabric of the scientific enterprise. Many of these treks will be in the Earth and environmental sciences, the field in which I have lived my scientific career. In particular, there will be many forays into that contemporary topic of almost universal interest – global climate change. Probably no other scientific topic has been more regularly in the spotlight during the 1990s than global climate change, and intense debate has swirled around it. The issues of focus at various times have been the reality of climate change, the causes, the consequences, and the political, economic, and social responses to it. As a global scale, complex, slowly developing phenomenon, it displays many of the fascinating facets of scientific uncertainty in general, and it shows how scientists work and thrive in an environment of uncertainty.

The scientific excursions laid out in this book can be thought of as outings in 'the garden of uncertainty', explorations of a vast and irregular tract comprising established plots of annuals and perennials, some newly plowed ground, rare specimens, weeds, thickets, and mazes. Each area of the garden reveals a different facet of uncertainty. And for every insight about uncertainty that one may draw from science, there is usually a parallel and equally revealing experience to be found outside the realm of science that should make readers realize that the scientific world is not so different from their own world. Indeed, science is an important, accessible, and empowering part of everyone's world.

In making comparisons and analogies with the uncertainties that exist in science and in everyday life, my goal is to help readers to understand and accommodate scientific uncertainty in much the same way that they deal with other uncertainties in life. I hope the reader will come away with the feeling that scientific uncertainty should cause no greater hesitation or doubt than do the multitude of other uncertainties that people regularly face and routinely accommodate in their lives. With a better understanding of scientific uncertainty, readers will be able to see through the clouds that sometimes obscure the value and relevance of science to societal issues. In the process of coming to understand uncertainty, they will become more self-confident in grasping what science can and cannot offer.

2 Uncertain about science

> This notion that "science" is something that belongs in a separate compartment of its own, apart from everyday life, is one that I should like to challenge. We live in a scientific age; yet we assume that knowledge is the prerogative of only a small number of human beings . . . . This is not true. The materials of science are the materials of life itself. Science is the reality of living, it is the what, the how, and the why in everything in our experience.
>
> Rachel Carson, in accepting the 1952 National Book Award for *The Sea Around Us*

Science, as Rachel Carson observed, is a part of the very fabric of life. It has its strengths and weaknesses, its successes and failures, its doubts and uncertainties. As scientists attempt to understand how a cell malfunctions to produce cancer, how a gene transmits information to guide an organism's development, how an ecosystem responds to urban sprawl, or how the entire Earth responds to long-term changes in the chemistry of its atmosphere, these investigations are enveloped with uncertainty at every stage. The uncertainty arises in many ways, and the nature of the uncertainty may change through time, but the scientific endeavor is never free of uncertainty.

Has science been debilitated by uncertainty? To the contrary, the successes of science, and indeed there are many, arise from the ways that scientists have learned to make use of uncertainty in their quests for knowledge. Far from being an impediment that stalls science, uncertainty is a stimulus that propels science forward. Science thrives on uncertainty. The uncertainty of how genetic traits were replicated led eventually to discovery of the double helix molecular configuration. Indeed, one might argue that it is *certainty*, rather than uncertainty, that impedes science. The protracted struggle in the seventeenth century by Copernicus, Kepler, and Galileo to overturn the notion that Earth was at the center of the solar system[1] was carried

[1] This history is recounted more fully in Chapter 6.

on in the face of the then-prevalent theological certainty that Earth occupied a very special place in the architecture of the universe.

The uncertainties that scientists face are really not so different from the uncertainties we encounter in everyday life. Risk-taking is extolled in many cultures as an attribute of a successful person. But risk arises precisely because of uncertainty. The willingness and ability to formulate and take action and accept risk in the face of uncertainty is considered a character strength. To be sure, there are risks taken that later prove unwise, but without risk-taking there is an implicit acceptance of the *status quo*. An unwillingness to be motivated by uncertainty is indeed a real barrier to progress.

Ironically, people who are not scientists often equate science with certainty, rather than uncertainty. They have been conditioned by the highly precise and accurate predictions of eclipses, of the daily progression of ocean tides, of the exact times of the local sunrise and sunset, of the clockwork precision of a spacecraft landing on a distant planet. Another aspect of certainty relates to reliability of technology when people pick up the telephone, turn on the television, or turn the ignition key in an automobile, there is an expectation that the device will work. Indeed, when things do not happen as expected or as predicted, there usually is some measure of surprise and discontent. Most people do not relish surprises and are, at some level, uncomfortable with unpredictability and uncertainty.

Certainty in other contexts is a source of contentment. Religious tenets that assure the faithful an afterlife assuage concerns about the abyss of death. Some political mantras, such as 'smaller government is better government' or 'there is no such thing as a good tax', relieve those who recite them from the burden of evaluating a wide range of public policy issues. Recasting a world full of shades of gray into a simpler and starker entity comprising only blacks and whites eliminates the difficult task of weighing nuance and replaces it with the comfort that certainty offers.

When scientists cannot demonstrate a high level of certainty in their understanding of complex natural systems, there is sometimes an undercurrent of impatience and discontent in the general public. In late 2001, bioterrorism in the form of anthrax spores appeared in government buildings and postal facilities in the USA. For a period of time, however, there was uncertainty and confusion in the public health community and at the National Center for Disease Control as to how exactly anthrax might be transmitted, what spore concentrations could be considered hazardous, and how anthrax spores could be rendered impotent. The public wanted answers that public health practitioners could not immediately provide. Similarly in the UK, an outbreak of foot and mouth disease in 2001 was met with a range of scientific opinion as to how it should be contained. Massive culling of neighboring herds was the containment strategy adopted, but scientific opinion was far from unanimous. Long after the disease waned, debate continued about whether the culling strategy was necessary or effective.

When scientists acknowledge that they do not know everything about a complex natural phenomenon such as the spread of disease through an ecosystem, the public sometimes translates that to mean that scientists do not know *anything* about the subject. That, in turn, leads to a loss of public credibility in the capabilities of the scientific community. A byproduct of the loss of credibility is an all-too-frequent willingness of the general public to entertain flimsy pronouncements from kooks, charlatans, and marginal skeptics. With an air of scientific authority and certainty, these pseudo-scientists make assertions that have never been subjected to the rigorous probing that is the foundation of genuine science.

Fortune-tellers, palm readers, clairvoyants, astrologers – the list could go on and on – all thrive on the inability or unwillingness of their clients to recognize the total lack of logical underpinnings and scientific observations in support of these practices. There is absolutely nothing that lends these charlatans any credence whatsoever. But their pronouncements are always carefully crafted to leave their clients with the impression that extraordinary powers have been objectively exercised. In the next chapter, I describe a particularly egregious example of this, a prediction of a major earthquake that was taken far too seriously by far too many people who should have known better.

There are, of course, serious scholars who challenge the notion that science is the only pathway to universal truths. One school of philosophy, loosely referred to as postmodernism, questions whether scientists are neutral and objective, and whether scientific knowledge is truly the outcome of unbiased rational thought. In extreme form, it questions whether a deterministic natural world exists outside of the mental constructs that humans erect. This perspective from the fringe views science as a game with a set of rules created by scientists, and argues that the apparent successes of science in understanding the natural world would not be defensible if we did not accept the rules of the scientific game. A subtheme of this position is that science is a self-serving concept and entity.

In 1996, the postmodern perspective was brought into sharp focus, and ridicule, when Dr. Alan Sokal, a professor of physics at New York University, submitted an article[2] for publication to a journal known to espouse this particular philosophy. The contribution carried the title *Transgressing the Boundaries: Towards a Transformative Hermeneutics of Quantum Gravity*, which seemed to convey a postmodern flavor. Because a physicist had submitted the manuscript, the editors of the journal welcomed the opportunity to publish an article by a scientist that seemed to erode the foundations of science from within. But the article by Sokal was a Trojan horse, a cleverly crafted hoax that illuminated not the philosophical frailty of the scientific method but rather the gullibility of the editors. Sokal had written a seemingly erudite essay, using convoluted language and structure, that really was nothing more than nonsense cloaked in pseudo-scientific jargon. The over-eager editors took the bait and published Sokal's article. Once it was in print, Sokal revealed the hoax. The implications of 'l'affaire Sokal', as it has been dubbed, are many, but for my purposes here the principal point is this: there are people,

[2] Alan D. Sokal, Transgressing the Boundaries: Towards a Transformative Hermeneutics of Quantum Gravity, *Social Text*, 1996.

educated and not, who simply believe that science has nothing special to offer. They are skeptical of, or simply ignore, scientific results.

There is another type of person who may accept scientific results in general, except when the science conflicts with other beliefs they hold dearly. While writing this book, I read the obituary[3] of Charles K. Johnson, president of the International Flat Earth Research Society. Aside from this particular obsession about the shape of the planet, Mr. Johnson seemed to have led a rather normal life as an airplane mechanic. His disagreements with the scientific community were few, except as they related to the shape of the Earth. The image of the spherical Earth taken by the Apollo astronauts from the moon was easily explained: the moon landings were an elaborately staged hoax, and the photograph was but a prop in that scam. We may smile at this quaint explanation, but the pool of uncertainty about science is deepened, little by little, by each and every Charles Johnson who successfully draws attention to his particular astigmatic view of the natural world. In 1994, a poll[4] showed that almost one in ten Americans thought the moon landings were faked. And Hollywood does not help matters with creations such as the 1998 film 'Wag the Dog', in which a US President seeks to divert attention away from personal impropriety by manufacturing a fake war against Albania, including a staged invasion with faked film footage depicting destruction and carnage.

A more widely known conflict between science and personal belief centers on the biblical account of creation in the Book of Genesis. The issue is whether the bible is literally true, word by word. Did God create the entire universe and every living creature in just six days? Geologists and evolutionary biologists make a persuasive case that not all modern life forms were present at the birthday of Earth, and that most of today's life has evolved from other life forms over the vast expanse of geologic time. But biblical literalists do not accept an iota of departure from the Book of Genesis. If Genesis is literally correct, then modern geology and biology must be wrong.

[3] *New York Times*, 25 March 2001. [4] Marc Fisher, *Washington Post*, 20 July 1994.

Creationists have now taken on the task of proving the tenets of evolutionary biology incorrect, through an endeavor they identify as 'creation science'. The so-called creation scientists have tried to identify flaws in the logic or observations of evolutionary biology so as to 'disprove' it. They have not, however, applied equal vigor to testing the hypothesis set forth in the Book of Genesis. They will not even acknowledge that the account in Genesis is even an hypothesis, let alone testable. They can conceive of no experiment, no observation, that might disprove Genesis. Therein lies the reason that the practitioners of 'creation science' are not really scientists. Creationists will never concede their fundamental position, that all living things are the direct and simultaneous creations of a supreme being. They cannot permit themselves to admit the possibility that the biblical account of creation might not be true or may someday be shown to be untenable. Practitioners of genuine science, by contrast, easily admit uncertainty and are very comfortable working in an uncertain environment. In real science, few concepts can ever be accepted as unquestionably true or absolutely certain.

Indeed, genuine science operates on the assumption that a concept *can* be shown to be false. Falsification occurs when a concept is shown to be logically inconsistent or runs counter to direct observations. Lynton Caldwell, in a review of Michael Zimmerman's book *Science, Non-Science, and Nonsense*[5], describes science as a process of "separating the demonstrably false from the probably true".[6] It is a fundamental underpinning of science that only falsehoods, not truths, can be proven. Truths are simply the survivors of multiple attempts at undercutting. In fact, science progresses in part by continually probing for the soft underbelly of concepts that may have some partial success in explaining some natural phenomena. The unending search for weaknesses may reveal subtle inconsistencies that ultimately require revision or rejection of the original concept.

[5]Johns Hopkins University Press, Baltimore, MD, 1995.
[6]*The Environment*, vol. 38, n. 6, p. 25, 1996.

PEER REVIEW

What is the environment in which these scientific confrontations take place? At the center is a process called peer review. When scientists wish to tell the world about some research that they have conducted, there is an established path to follow. Often the first step is to make an oral presentation of their research at a professional society conference. This requires the prior submission of a very short written summary of their contribution to the committee organizing the program of the conference. This summary is then published in the program so that others may decide whether they want to attend the presentation. At the conference the author will typically make a ten to twenty minute presentation of his or her work, after which there may be questions or discussion from the audience. The opinions expressed in the discussion range widely: agreement, disagreement, skepticism, praise, ridicule.

Should the scientist feel sufficiently encouraged by the discussion in the oral presentation, he or she may then prepare a longer written report of the work and submit it for publication to a scholarly journal. The editor of the journal, in turn, sends the manuscript to other practicing scientists working in the general area of the submitted contribution, asking their opinion about the suitability of the work for publication. The peer reviewers are asked to assess the work from a number of perspectives. Is the work novel and original? Is the methodology employed suitable for the research purpose? Are there errors in the experimental design or in the theoretical derivations? Do the conclusions follow directly from the observations or data presented? What is the level of uncertainty that accompanies the results? This vetting of research reports by experienced practitioners acts as a filter that rejects flawed research but allows research that meets a certain standard to be published for others to read, evaluate, contest, or replicate. Virtually all research articles that are published in professional journals have passed the test of peer review.

The peer review process is not infallible, but the successes of peer review in filtering out weak or flawed science far outnumber the occasional failure. Sometimes peer review will give the benefit of the doubt to a particularly important claim that later proves incorrect, but the process allows for self-correction. In 1999, a team of physicists presented experimental evidence for the existence of a new super-heavy element, number 118 in the periodic table of the elements. Experimentalists in other laboratories, as well those in the original group, tried to reproduce the result by repeating the experiment, but with no success. After two years of failure, the original team published a withdrawal of their claim, acknowledging that they may have misinterpreted the data in their first experiment. Again in early 2002, a paper was published in a very prestigious journal that claimed to observe evidence of nuclear fusion as small bubbles formed and then imploded in an organic solvent when excited by sound waves.[7] In the peer review process, the paper proved to be very controversial, but because the outcome of the experiment, if true, had such extraordinary implications the editors decided to publish the paper. To be sure, the experiment will be repeated in many other laboratories by scientists keen to verify or invalidate the reported results.

A media newcomer, the Internet, has presented a significant challenge to peer review. Anyone with a computer can place his or her research, sound or flawed, relevant or irrelevant, significant or trivial, into the public domain for anyone to read. This places a much greater burden on the consumer of this research to review and evaluate it. The gate-keeping role of peer review that filters out flawed research and prevents it from being published in the scientific journals now falls to every individual reader surfing the Internet. The Internet is a great leveler in that anyone can post almost anything, but the task of deciding whether what is posted has any truth or value falls to the individual user. In earlier times prior to the development of the Internet, the opportunity to make available one's thoughts and ideas to the general public without passing editorial review was a privilege available only to the wealthy, who could self-publish via a vanity press.

[7] Taleyarkhan, R. P. et al., Evidence for nuclear emissions during acoustic cavitation. *Science* vol. 295, pp. 1868–1873, 2002.

The shifting of the burden of evaluation to every individual browsing the World Wide Web makes a public understanding of science and uncertainty ever more imperative.

SOWERS OF UNCERTAINTY

People who do not like what science is telling them often mount subtle and not-so-subtle assaults on science. These take the form of attacks on particular research outcomes that they find threatening. They often argue that had the science been 'properly' conceived and executed, a different result (implicitly meaning one more to their liking) would have emerged. The code-words that frequently identify this particular attack on scientific credibility are 'unsound science', 'unsettled science', 'uncertain science', 'poor science', 'junk science', and the like. What distinguishes these criticisms from those leveled by peer review is that they take place outside of the usual scientific channels and standards. These criticisms appear in newspapers via paid advertisements and letters to editors, and through participants on radio and television talk shows.

These code-word descriptions are used regularly by the petroleum and coal industries as they comment about the causes and consequences of global climate change. In a series of prominently placed op-ed advertisements, the ExxonMobil Corporation[8] frequently denigrates scientific research that documents climate change or that offers evidence that the use of fossil fuels[9] may be contributing to the change. As one of the largest of the international oil companies, ExxonMobil has a strong interest in forestalling a turn away from fossil fuels, and accordingly it has tried to slow legislation or derail international treaties that might limit emissions of carbon dioxide and other 'greenhouse gases' to the atmosphere. One might imagine that if the fossil fuel industry had significant scientific observations that

[8] See, for example, the *New York Times* for 23 March, 10 August, and 21 September 2000.

[9] Fuels such as coal, petroleum, and natural gas are called fossil fuels because they were formed long ago by geological processes. They reside in the rocks making up the crust of the Earth, and they are extracted by mining or pumping from the surface.

contested the role of greenhouse emissions in climate change, they would fight the battle in the scientific coliseum, the peer-reviewed journals where scientific debate routinely occurs, rather than in the media or on the streets. But the fossil fuel industries are more interested in winning the political battles in London, Berlin, Washington, and the state capitals; they spend lavishly in the public arena to confuse and thus undermine public confidence in scientific results.

The strategy of casting doubt and uncertainty about science to influence highly placed decision-makers has not been in vain. In March of 2001, Christine Todd Whitman, the newly appointed Administrator of the Environmental Protection Agency (EPA) in the George W. Bush Administration, abandoned the more stringent limits on arsenic in drinking water that had been promulgated by the previous administration and began a re-evaluation of the scientific basis on which those rules had been framed. "We will use strong science . . . to determine what the new limit should be."[10] Such a statement had only one purpose: to undermine public confidence in the previous scientific research on which the newly rescinded regulations had been structured. Those regulations were preceded by more than a decade of reviewing the science addressing arsenic in the environment and its effects on public health, and the publishing of a report on arsenic from the US National Academy of Sciences. That apparently was not sufficient to overcome the opposition from the mining industry, which discharges arsenic as a byproduct of certain types of ore processing, and from communities that would need to upgrade their purification systems if they wanted to continue to drink well water. Of course the EPA only echoes the position of the White House. "We're going to make decisions based upon sound science, not some environmental fad or what may sound good" said President George W. Bush to a group of Environmental Youth Award winners gathered on 24 April, 2001 for a ceremony in the State Dining Room of the White House.[11] Six months later, the National Academy of Sciences, after reviewing the evidence

[10] *New York Times*, 21 March 2001.
[11] http://www.whitehouse.gov/news/releases/2001/04/20010424-1.html

again at the request of the Administration, confirmed that new lower limits for arsenic were entirely justified, indeed perhaps not stringent enough. Of course, no new scientific data, no additional 'sound science' had appeared to support the implication that the previously promulgated revisions had been based on unsound science.

These attacks on science are hardly new phenomena. In 1952, when Rachel Carson asserted that the widely used pesticide DDT was having a devastating effect on avian reproduction,[12] the pesticide industry derided her position as being based on weak science. For decades, the tobacco industry denied there was any scientific evidence that showed that smoking was hazardous to health. In the 1970s when the debilitating health effects of lead in the environment came to be recognized, the producers of gasoline that contained lead ridiculed the science. When acid rain in the northeastern states of the USA was found to be a consequence of burning high-sulfur coal in electrical power plants in the Midwest, the electrical generating industry scoffed at the research. When confronted in the 1980s with allegations that chlorofluorocarbons (CFCs) were destroying stratospheric ozone, the chemical industry argued that the science behind the allegation was weak and inconclusive:

> The international chemical industry vigorously denied any connection between the condition of the ozone layer and increasing sales of CFCs. Industry forces quickly mobilized their own research and public relations efforts to cast doubt on the theory.[13]

While the public relations campaign confused the public, the science stood ever firm. In 1995, the Nobel Prize for chemistry was awarded to Sherwood Rowland, Mario Molina, and Paul Crutzen for the research that shed light on the mechanism by which CFCs caused ozone

[12] *Silent Spring*, Houghton Mifflin, New York, 1952.
[13] Footnote reference to Dotto and Schiff, *The Ozone War*, pp. 149–165, by Richard Elliot Benedick in *Ozone Diplomacy*, p. 12, Harvard University Press, Cambridge, 1991.

depletion. This was the first and only time the Nobel Prize has recognized research in environmental chemistry.

Does all peer-reviewed scientific research qualify as great science? Of course not. I read scientific journals regularly, submit research reports for publication, and do peer review for them as well. Most scientists will acknowledge that along with the abundant significant research results, the journals contain some correct but trivial contributions, and a few others that later prove to be flawed in methodology. Occasionally, but very rarely, even a fraudulent submission, describing work never done or results never achieved, slips through, only later to be unmasked when someone cares enough to question and check it. To be sure, scientists do not want unsound, careless or poor science cluttering the journals and confusing the state of knowledge. But *uncertain* science, *unsettled* science, is hardly the same as unsound science. The normal state of affairs in science is unsettled and uncertain, and no amount of new research will completely eliminate uncertainty. As earlier questions are answered, new questions appear. Lest this sound like a treadmill of futility, let me assure you that it definitely is not. Far from being frustrated or debilitated by uncertainty, scientists derive strength and creativity from uncertainty. Uncertainty is a challenge, a catalyst for scientific progress.

"PEOPLE LOVE SCIENCE. THEY JUST DON'T UNDERSTAND IT"

Why do so many people have such a hard time accepting and accommodating scientific uncertainty? Are there deeper reasons that go beyond the comforting certainty of religious faith, the apparent certainties offered by charlatans, or the confusing smokescreens floated by some industries trying to protect their economic interests? Much of the problem, I believe, lies in the fact that most people lack an elementary understanding of science generally. This scientific illiteracy provides fertile ground for the appeal of certainty and the confusion of uncertainty to take root.

C. P. Snow, in his famous book *Two Cultures*,[14] outlined the gulf of understanding that separates science from the arts and humanities in the modern university, and in society generally. This view was foreshadowed by Rachel Carson in the quotation that opens this chapter. A 1996 article[15] addressing science education in America began with the statement, "Americans love science, they just don't understand it". Indeed, one can often hear the pessimistic view that the general public will never understand science, let alone the subtleties of uncertainty. Were we not walking on such thin ice of scientific understanding, would we be so vulnerable to the pronouncements of kooks or the smokescreens of confusion laid out by special interests? If we were not so unfamiliar with science, perhaps such obfuscation would not take hold so easily.

The problems with understanding science begin very early, with some inadequacies in the educational system. In a very important sense, children are born as natural scientists. They emerge into a strange world and are curious about everything surrounding them. They look, they touch, they listen, smell, and taste. They make observations of this new world, and they process and evaluate the stream of information coming at them from every direction. They explore, experiment, and learn from their mistakes. Then they go to school.

Schooling in the USA, at least as far as scientific inquiry is concerned, introduces children to a new methodology. The new methodology focuses on science not as a continuation of the curiosity and explorations children make as toddlers. Rather, science in school is, more often than not, presented as a recitation of accomplishment rather than as a process of inquiry. Facts are paramount. Students are told the world is round; Earth orbits the Sun; there are 365 days in the year; insects have six legs; the Amazon is the world's biggest river; Mt. Everest is the highest mountain; rocks can be segregated

[14] *Two Cultures and the Scientific Revolution*, Cambridge University Press, 58 pp., 1963.

[15] Michael Carlowicz, *EOS Transactions of the American Geophysical Union*, 27 August 1996.

into igneous, metamorphic and sedimentary categories; atoms have protons, neutrons and electrons. The new emphasis is on stuffing little craniums full of 'facts' that someone has determined every well-educated person must know. Science is presented as answers rather than as questions. Relegated to the distant background is the process of inquiry, of how 'facts' are determined, of how durable or transient 'facts' may be, and of how certain or uncertain we believe them to be.

Answers, as I noted earlier, are to some people more comforting than questions. Uncertainty in a simple context might translate into "It could be this or it could be that", but such a perspective is often seen as being dangerously close to the pit of cultural and moral relativism, where shades of gray between right and wrong can lead young minds astray. "No", say the cultural absolutists, "there are things of which we are certain, and don't try to confuse the issue with uncertainties that only obscure the truth."

TESTING, TESTING . . .

The success of schooling is often measured with standardized tests administered to students locally and nationally, to gauge achievement in reading, math, and science. Some school systems and their teachers are ranked according to the success or failure of students in such standardized tests. Proposals are regularly floated to link the governmental funding of schools to their performance on standardized tests. It should come as no surprise that some schools now 'teach to the test', recognizing that their political and perhaps financial support may depend on doing well on these tests. From an international perspective, however, even teaching to the test has not produced dramatic results from US schools. The eighth graders (age thirteen students) in 1999 scored below the international median in both science and mathematics in the Third International Mathematics and Science Study (TIMSS), which tested students in twenty-three countries.[16] Within the USA alone, the National Assessment of Educational Progress

[16] http://ustimss.msu.edu/

every few years administers a mathematics test to fourth, eighth, and twelfth graders (ages nine, thirteen, and seventeen, respectively), with results categorized as 'below basic', 'basic', 'proficient', and 'advanced'. In the test given in 2000, only one in three nine- and thirteen-year-old students and fewer than one in five seventeen-year-old students reached the proficient level.[17]

I recognize of course that scientific progress, indeed progress in any of life's endeavors, must have an educational foundation that includes basic literacy and numeracy. Reading, writing, and quantitative skills surely must be included in a list of life's essentials. But as necessary as they are, if they alone are the targets of education, we will shortchange both the students and the society they are a part of. Other important skills – how to observe carefully, how to think critically, how to deal with conflict, how to develop teamwork – are not easily tested but arguably are equally important, or more so, to the success of students and to their community.

This emphasis on acquiring 'knowledge' persists throughout the primary and secondary educational systems and continues unabated in many higher education curricula. Textbooks for the introductory survey courses in science too often are dull compendiums of what we *do* know, but without a stimulating summary of what we *don't* know. Where are the frontiers of science described in these textbooks? What are the unanswered questions that might excite imaginative students and rekindle the natural curiosity they had as young children? Why do they not learn of the uncertainties in the field?

The history of how a field of science has evolved over time can be revealing of the false starts, the blind alleys that scientists followed in times past. Antonio Machado, a Spanish poet of the early twentieth century, captured this idea when he wrote: "Traveler, there is no road. You make the road as you go." Although the history of a discipline is usually not couched in terms of the uncertainty that enveloped the field, it can highlight the conventional wisdom of a

[17] *New York Times*, 3 August 2001, p. A21; *New York Times*, 21 November 2001, p. A12.

certain time and show how, in the face of conflicting observations and competing ideas, that conventional wisdom began to unravel, only to be replaced with newer concepts. What the perspective of time and history offers is an opportunity to see how science as a field of *inquiry* has evolved, and how probing questions and critical thinking contributed to better understanding. Without any historical context, students must settle for a snapshot of today's answers, not yesterday's or tomorrow's questions.

In the graduate degree programs, where in principle we train the professional scientists and future professors, universities must try to undo all of this. By the time students reach graduate school, they have focused far too long on giving answers instead of asking questions. They have a hard time formulating a research project that poses an interesting non-trivial question, and that lays out a pathway that may shed some light on it. Many of my scientific colleagues in the university are not helpful in freeing students from the educational constraints that have dulled their curiosity. Although many faculty members themselves have a vision for their research, too often they view graduate students as cogs in their personal research machine. The student is not asked to formulate a research question and an approach to answering it. Instead they are assigned a project, narrow in scope, seldom explained in the context of the larger research vision. The students are instructed on how to make use of the most sophisticated research equipment to measure this or that but are left out in left field as far as the relevance of the measurements is concerned. They learn a lot about how, but little about why. And, of course, when the technical skills they have acquired are made obsolete with the next generation of instrumentation, many will fall away from science disillusioned.

So why do we have so much science illiteracy? Why are people so susceptible to simplistic ideas and false assertions? Why are they puzzled by scientific uncertainty? In part, I think it is because the science education that most students receive stifles their natural scientific instincts. Many students lose interest in science in the primary and secondary schools because it does not take advantage of their natural curiosity. The higher educational system then perpetuates the problem, graduating science 'majors' who have absorbed all the 'facts' but who are not equipped to challenge them. The same stultifying system trains new elementary and secondary school teachers, who repeat these patterns, and at the postgraduate level trains new scientists as capable executors but not imaginative formulators. In short, educational practices common in many countries have led to a widespread adult population that is interested in and yet puzzled by science, principally because they do not understand how scientists go about the business of asking questions and evaluating answers.

Continuing the metaphor of the garden of uncertainty, we have started our tour in the orientation pavilion, where the displays have illuminated some of the sociological, political, and educational facets of science and uncertainty. The next chapter remains set in the orientation pavilion, where we will focus on a special institution that stands between science and the public: the mass media. Can the media help to convey science to the public, not simply in terms of accomplishment, achievement, and certainty, but rather as a process or method of inquiry that is stimulated by failure and which flourishes in the dim gray light of shadows cast by uncertainty?