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IMAGINARY GARDENS WITH REAL TOADS

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MARIANNE MOORE SAID: "Poetry is about imaginary gardens with real toads in them." That applies just as well to many aspects of human cultures and especially to science. Scholars and scientists of all kinds are gardeners of ideas, trying to cultivate lovely flowers and fruits of understanding. Such intellectual gardeners usually pay little attention to toads or other uninvited creatures residing among the flowers—unless those creatures begin to munch or trample the plants. Visitors who seem greatly concerned about the toads but unappreciative of the fruits and flowers naturally dismay the gardeners, especially if such visitors even mistake the gardeners for toads.

This horticultural whimsy explains my title and offers rustic metaphors for some of the phenomena addressed in this volume. In my view, the blossoming of "science studies" by historians, sociologists, and philosophers is to be welcomed. It is seeding fallow fields that have long separated scientific and humanistic gardens. In the process, some dust and mud is being stirred up, coating alike flowers and toads. That is inevitable. Science has always drawn lively critics, often motivated by ideology or mysticism. However, I am startled to find a philosopher suggesting that Newton's ***Principia*** could be regarded as a "rape manual," or radical postmodernist scholars asserting that scientific discoveries are "socially constructed fictions." Such claims, and the disregard for rational analysis that often indulges them, deprecate not only science but all objective scholarship and public discourse. As in horticulture, blights readily spread to neighboring gardens.

In this paper, my chief aim is to welcome any visitors or critics, friendly or not, to tour three patches of my personal scientific garden. The first deals with what for me was a rehearsal for this conference. It was a public television program, titled "The Nobel Legacy" and aired last May, in which I had to counter doleful complaints about science delivered by Anne Carson, a poet and professor of classics at McGill University. The second part comments on aspects of scientific work that are often misunderstood. These pertain to science education as well as to the pursuit of new knowledge. The third part sketches a saga of scientific discovery, submitted to exemplify favorite themes and to confound postmodern nihilists. I conclude by emphasizing the kinship of natural science with other liberal arts.

A few caveats. For brevity, I say just "science" when usually I mean to include all or most of natural science, mathematics, and some engineering and technology. I do not mean to include social science; that would stretch too far my unruly metaphors and commentary.

SCENES FROM *THE NOBEL LEGACY*

The television program was part of a trilogy comprising Medicine, hosted by J. Michael Bishop; Physics, hosted by Leon Lederman; and Chemistry, hosted by me. The series was directed by Adrian Malone, known for his many previous science productions, including "The Ascent of Man" with Jacob Bronowski and "Cosmos" with Carl Sagan. As described in a synopsis, *The Nobel Legacy* "seeks to reveal the beauty and humanity of science to audiences not generally drawn to science programming . . . and [to] encourage viewers to become more aware of the scientific strides transforming their lives." Each segment featured one or two scientists whose work ushered in major revolutions: Jim Watson and Francis Crick, Werner Heisenberg, Antoine Lavoisier, and Robert Woodward, my late colleague at Harvard who transformed synthetic organic chemistry. The filming was done at sites of great historical or esthetic interest, ranging from Venice, Florence, and Paris to Hawaii and Carlsbad Caverns.

Anne Carson appears in two or three scenes in each of the segments. Her role was "to provide a provocative philosophical counterpoint . . . the spark of dissenting opinion." Typical of the sparks she struck were her scenes in the Chemistry program. It opens with Carson in Paris, on a bridge over the Seine, and she says:

> The Nobel Prize idealizes the notion of progress. My problem is that I don't believe in progress, and I am skeptical of how chemistry is contributing to my humanity. . . . Now that we've filled the world with Styrofoam cups, carbon monoxide and holes in the ozone, maybe it's time . . . to stand still and pay attention to the real relation between our humanity and our progress.

From this beautiful scene, there's a quick flash, without explanation, to the guillotine (in anticipation of Carson's later description of Lavoisier's execution). Next Carson appears at the Institute de France, the famous "home of the immortals." She explains that it was previously a school attended by Lavoisier, and continues:

> Before the Revolution this place had a reputation for reason . . . Lavoisier's teachers believed that using the light of reason, old ideas and superstitions could be burned away . . . [and] a truly rational society lay around the corner.

As she stands by the bust of Lavoisier, with ominous flashbacks to the guillotine punctuating her sentences, she delivers a scornful verdict:

> What an irrational idea. . . . This happy delusion that there are such things as facts, and they do not deceive us, underlies the whole progress of science and chemistry down to the present day.

A later scene, my favorite among hers, has Carson in the lovely garden within the inner courtyard of the Gardner Museum in Boston, where she says:

> Like every science, chemistry promises to use technology to bring us to paradise. . . . This garden is a little like paradise. It's a small enclosed area of symbolic perfection, an illusion created by the idea that you can have perfect control of nature and all external conditions. It would be a mistake to confuse that illusion with reality, or to think that tinkering with the chemistry of the human condition can ever bring us to paradise. I don't want scientists messing around in the garden of my soul.

Some of my scientific colleagues were quite annoyed with Anne Carson; they regarded her remarks as nonsensical, a silly distraction.[1] Others were annoyed with me, because in interviews I defended her role in the program.[2] I regarded it as a forthright way to acknowledge grim concerns that many people have, misplaced as some of them are. At the outset of the filming, I thought it odd that Adrian Malone did not allow the scientists serving as hosts to reply directly to Carson's criticisms. He wanted to maintain dramatic tension. Later, I came to appreciate that, at least for TV, his indirect approach was more effective. It left the hosts free to extol the wonder and beauty of science and to give our own perspective on toadish issues like pollution. Likewise, it invited the viewers to think for themselves about the issues rather than passively watching a battle of sound bites.

NOTES FOR A CONVERSATION

Someday I would like to meet Carson and discuss her concerns, with the hope of understanding them better. As Malone liked to emphasize, TV is an emotional medium, not suited to comprehensive explanations. Having experienced that, I do not suppose Carson is so dogmatic as some of the caustic lines she delivered on the program. In any case, again I do not feel obliged to refute her comments directly. Instead, I offer here notes on six points I would want to bring up if I ever do have the opportunity for a conversation with Anne Carson.

1. However questionable the moral or spiritual progress of humanity may be, science has vastly enhanced our capacities and perspectives. As just one example, plucked from a cornucopia, consider the germ theory of disease.[3] For millennia, humankind was almost helpless to combat frequent epidemics of infectious diseases. Two of Pasteur's five children died of typhoid fever, not an uncommon toll in his time. His work establishing the germ theory transformed medicine. Beyond the enormous practical impact of the vaccines thereby developed, the conceptual advance opened the way to the incredible modern era of biomolecular science. Ultimately, this will profoundly impact cultural perspectives too. Just as the Copernican revolution drastically recast mankind's place in the outer world, the "DNA revolution" has transformed our conception of life's inner cosmos.

Exhilarating as they are, the achievements of science cannot create an earthly paradise or even a humane civilization. Much beyond science is required for that. Today, about two million children die each year of diseases for which vaccines are already available.

2. Most scientists would agree with Carson's concerns about toads nurtured in the gardens of science. Our modern technological society has fostered reckless proliferation of people, weapons, pollution, and environmental damage. These are not inevitable consequences, but cannot be overcome without unprecedented economic and political initiatives. Such problems have often plagued preindustrial societies too.

The specialization and sophistication of modern technology have induced another pervasive anxiety. People understand less and less about the many machines, techniques, and underlying concepts on which they depend. This has increasingly serious political consequences; it prevents objective assessment of important questions of public policy involving science, and fosters both distrust and credulity. Here science education, which I discuss later, has a crucial task.

3. There is another kind of pollution, not spawned by science, and far more terrible and intractable than any chemical garbage. It is a pollution by words, toads in humanistic gardens. Perceptions shaped by the power of words have given rise to countless wars and all sorts of political and social folly. Most often that power is illegitimate, not drawn from objective referents. Science can seldom solve sociopolitical problems. Yet sometimes it can change conditions enough to enable resolution, or provide evidence and analysis to help contend with wordly pollution.

4. The notion, advocated by Francis Bacon, that the aim of science is to attain "power over nature" has long drawn attacks as a foolish and arrogant quest. In my view, the aim is not control but comprehension. When science enables us to cope better with microbes and lightning bolts, we should be grateful. When it lets us glimpse more deeply into mysteries of Nature, we should be awed.

At a time when lightning was considered a divine punishment, Ben Franklin gave a sparkling response to a critic of his lightning rod:

> He speaks as if he thought it Presumption in man, to propose guarding himself against the Thunders of Heaven! Surely the Thunder of Heaven is no more supernatural than the Rain, Hail or Sunshine of Heaven, against the inconveniences of which we guard by Roofs & Shades without Scruple.[4]

The alleged arrogance of science also does not accord with what I regard as the most important aspect of the modern scientific "world view." As stated by Richard Feynman: "Science is not about what we know; it's about what we don't know." Science lives at its frontiers, looking to the future, aware of the enormous scope of our ignorance.

This is painfully evident in medicine; Judah Folkman, a distinguished physician, points out that the medical encyclopedias describe some fifteen to twenty thousand recognized human diseases, but fewer than a thousand can be "cured" or completely reversed.[5] Many more cannot be affected at all by modern medicine, even to relieve symptoms. That is what allows "alternative medicines" to flourish, some of it outright fraudulent.

5. Before our conversation, I would recommend to Anne Carson, as I do to my science students, a wise and delightfully engaging book: *The Limits of Science* by Peter Medawar. In particular, Medawar points out that, while Bacon is identified with seeking power over Nature, his writings have "many more typical passages in which he advocated a much more humbly meliorist position," and quotes from his preface to *The Great Instauration*:

> I would advise all in general that they take into serious consideration the true and genuine ends of knowledge; that they seek it neither for pleasure, or contention, or contempt of others or for profit or fame, or for honor and promotion; or suchlike adulterate or inferior ends: but for the merit and emolument of life, and that they regulate and perfect the same in charity: for the desire of power was the fall of angels.[6]

Like most philosophers and all politicians, Bacon said different things at different places. But I do believe that this statement, rather than any urge to control nature, and despite familiar human frailties, represents the chief motivation of most scientists. Recently, Henry Rosovsky proposed, in discussing university governance and contentions, that there should be a creed that professors subscribe to just as do physicians.[7] Perhaps Bacon's preface might serve for any field of scholarship (although I could not forswear seeking knowledge for pleasure!). It would be interesting to find out how Carson and other critics of science might respond.

6. Another book I especially recommend, both to scientists and critics, is *Science and Human Values* by Jacob Bronowski. It comprises three eloquent essays, devoted to showing that science imposes "inescapable conditions for its practice" which compel an ethic. Far from being neutral with respect to human values, science like art requires freedom, honesty, and tolerance in order to foster originality and creativity. Bronowski was both a scientist and author of a major study of William Blake, a Romantic poet vehemently hostile to science. In the revised edition of *Science and Human Values*, Bronowski added a dramatic dialogue, "The Abacus and the Rose." This presents a vigorous debate between a literary scholar, "bitter because he feels helpless in a changing time," and a molecular biologist, "slow to see that there really are other points of view." In his preface, Bronowski says he tried "to put the arguments on each side fairly . . . in words which do not caricature its case." As the conversation spirals between the two cultures, their perspectives gradually intertwine and become complementary. Bronowski concludes with a sonnet; his first lines are:

> I, having built a house, reject
> The feud of eye and intellect,
> And find in my experience proof
> One pleasure runs from root to roof

This humane unity in spirit, more often praised by scientists[8] than others, should be more widely acknowledged.

SOME METAPHORS FOR SCIENCE

At its frontiers, science-in-the-making is inevitably a messy and uncertain business, easily misunderstood by policy makers, funding agencies, reporters, students, and sometimes even the researchers. Those who decry science often confuse its rude frontiers with its civilized domains or foundations. Many examples of such confusion, inadvertent or deliberate, are noted and analyzed in *Higher Superstition* by Paul Gross and Norman Levitt and in *Science and Antiscience* by Gerald Holton. Here I simply outline aspects of frontier science that I think should be considered by anyone approaching it, pro or con. My sermonette begins with three favorite metaphors: language, pathfinding, and puzzle solving.

1. Nature speaks to us in many tongues. They are all alien. In frontier research, the scientist is trying to discover something of the grammar and vocabulary of at least one of these dialects. To the extent the scientist succeeds, we gain the ability to decipher many messages that Nature has left for us, blithely or coyly. No matter how much human effort and money we might devote to solve a practical problem in science or technology, failure is inevitable unless we can read the answers that Nature is willing to give us. That is why basic research is an essential and practical investment, and why its most important yield is ideas and understanding.

The language metaphor occurred to me when I received a letter in Braille. We are all born blind to Nature's language, and it takes much persistent groping and guessing to learn something of it. Ironically, our academic science courses inhibit the willingness of students to guess. In my teaching, I try to counteract that with questions that cannot be approached otherwise. Also, I tell my students:

> Not so many years from now, most of you will be considered expert in something. Then you will find that clients often come to ask your opinion, not because of what you know, but because they think as an expert you can guess better than they can.

Of course, the expert must also devise means to test the guesses. That is a crucial part of science; like children playing with new words, we want to try to converse with Nature. In some fields, few of Nature's words are yet known; in others, many volumes.

2. Science is often described as finding a way up an unexplored mountain. This emphasizes a tremendous advantage enjoyed by science: the goal, call it truth or understanding, waits patiently to be discovered at the top of the mountain. Thus marvelous advances can be achieved by ordinary human talent, given sustained effort and freedom in the pursuit. Far more formidable are enterprises such as business or politics; there the objectives may shift kaleidoscopically, so a brilliant move often proves a fiasco rather than a triumph because it comes a little too soon or too late.

The patience of scientific truth has another important consequence, often puzzling to the public. Frequently, what might appear as the most promising path up the mountain does not pan out; there are unanticipated roadblocks. Then it is vital to have some scientists willing to explore unorthodox paths, perhaps straying far from the route favored by consensus. By going off in what is deemed the wrong way, such a maverick may discern the right path. Hence in science, it is not even desirable, much less necessary or possible, to be right at each step. Since the truth waits patiently, and we must grope for it, wrong steps are intrinsic to the search. Adventurous scientists are heading in wrong

directions much of the time, optimistically looking for new perspectives that may show the way up the mountain.

Again, this pathfinding contrasts markedly with introductory science courses. Many students have told me about a disheartening syndrome: the questions and problems seem to have only one right answer, to be found by some canonical procedure. The student who does not quickly grasp the "right" way, or finds it uncongenial, is soon likely to become alienated from science. There seems to be very little scope for a personal, innovative experience. Nothing could be further from what actual frontier science is like. At the outset, nobody knows the "right" answer, so the focus is on asking an interesting question or casting the familiar in a new light. In my freshman chemistry course, I explain this to the students and ask them to write poems about major concepts, because that is much more like doing real science than the usual textbook exercises. I also show them quite a few poems that pertain to science, often without intending to. For instance, here is a quatrain by Jan Skacel, a Czech poet:

> Poets don't invent poems
> The poem is somewhere behind
> It's been there a long long time.
> The poet merely discovers it.[9]

This is the crux of our pathfinding metaphor. I hope the poems help students realize that there is much in science that transcends its particulars.

3. Science is also often likened to assembling a giant jigsaw puzzle. This metaphor was invoked by Michael Polanyi in his classic essay on the organization of scientific research, "The Republic of Science." He envisions competing teams with exactly the same talent, some structured in the hierarchical ways customary in practical affairs but one enjoying the chaotic freedom of science. In the hierarchical organizations, the team would be divided into units directed by a chain of officers; one unit might focus on yellow pieces of the puzzle, another on blue pieces, etc. Each unit would report up the chain of officers to a central authority that assigns tasks. Science proceeds very differently and much more efficiently. Each unit is on its own, free to look at whatever parts of the puzzle interest it. Nonetheless, the independent units are coordinated by "an invisible hand," because each has the opportunity to observe and apply the results found by the others. This creates a community of scientists that fosters and amplifies individual initiatives. Such a community, as Polanyi says, is "a society of explorers, poised to examine any new understanding of Nature."

Again, there is an ironic contrast between such intrinsic cooperation and the artificial competition among students that is imposed in typical courses. In my general chemistry course, we use an absolute grading scale, so students compete against my standard, not each other. Also, some work is designed to be done by teaming up with other students. Of course, in research there is some competition, but it is superficial in the context of the essential collaboration with predecessors and colleagues. Since results are reported openly, the work of a competitor often proves especially helpful, as it is likely to provide a complementary perspective.

IMAGINARY TOADS IN REAL GARDENS

As suggested by these metaphors, creativity in science has much in common with the arts. New insights often seem strange and idiosyncratic; blunders and breakthroughs at first look very much alike. The typically fitful evolution of germinal work into a widely accepted paradigm or movement is also in some respects similar for science and the arts. These aspects were brought out clearly by Thomas Kuhn[10] as well as Michael Polanyi.[11] Both wanted to counter simplistic depictions of the scientific method as a rather mechanical collecting of facts and calmly logical testing of hypotheses. In my laboratory, visitors are reminded of this theme by an epigram of Vladimir Nabokov: "There's no science without fancy, and no art without facts."

Such cheerful bows to the artistic qualities of science may be considered damning by critics like radical cultural constructionists and postmodernists. Among them some think that the political, class, and gender bias of scientists renders them incapable of finding objective knowledge about Nature. Those critics cannot imagine that toadish scientists could discover real gardens.

When asked to refute Bishop Berkeley, Ben Johnson simply kicked a rock. To a cultural constructionist, we might likewise point out an airplane, say. Rather than being limited to "socially constructed fictions," the natural sciences attain objective truths by functioning as a constructive society. A major part of Michael Polanyi's *Personal Knowledge* is devoted to showing in detail just how this works, despite human frailties and cultural contingencies.

For brevity, again I invoke my horticultural whimsy. In essence, the validity and range of applicability of new knowledge is established by examining many generations of its progeny, when it is mated with other plants already well established in the garden. In this propagation, errors are revealed as unviable mutations and die out. The stock that emerges is hardy, but not an eternal, universal tree of knowledge. Eventually, it will be hybridized anew to produce further progeny. Any part of the garden (as well as the toads) can be transplanted to another culture, so long as it gets suitable care, sun and soil there.

Now I turn from genial horticulture to consider the rape motif favored by Sandra Harding.[12] Like many scientists, male and female, I am sympathetic to feminist issues. But not to Harding's notion that Newton's *Principia* could be regarded as a "rape manual," later generalized by comparing science to "marital rape, the husband as scientist forcing nature to his wishes." As noted already, like Medawar and Bacon in his meliorist mood, I do not regard "forcing nature" as an aim of science. Certainly, it is absurd to tar Newton with that; he was an extremely pious fellow who regarded his work as revealing a divine order. For me, the chief lesson of all natural science, typified by Newton's mechanics, exalts Nature: she is the boss; we try to discover her rules; she lets us know the extent to which we have done so. Harding should consider Richard Feynman's remark:

> For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled.[13]

This was the last sentence of his report on the tragic explosion of the Challenger space shuttle.

Science, like so much else, has often been marred and misled by sexual bias.[14] It is thus gratifying that embryology now indicates the Garden of Eden story needs to be recast, as Eve came before Adam.[15] For its first thirty-five days in the womb, every human fetus is female, whether or not it has XX or XY chromosomes. On about the thirty-sixth day, a genetically programmed switch kicks in. For a normal XY fetus, some already developing female structures then fade away and male structures begin to form. In rare cases, however, the switch is defective; the XY fetus then continues on to become a woman, with external anatomy correct in all respects, although infertile. (Olympic athletes have since 1968 been subjected to a chromosome test, and allegedly a number of XY women athletes have been barred from competing.)[16] The most common defect in the genetic switch has recently been shown to occur on a single amino acid residue, at a critical location on the Y chromosome.[17] In fact, that defect is a missing methyl group, just a carbon atom with three attached hydrogen atoms. Thus, a single methyl group can determine the sex of an XY fetus. If it were missing much more often, human males might be as outnumbered as male bees or ants.

This evidence, indicating Eve's primacy and shrinking Adam's rib to a methyl group, was found by male scientists. Ultimately, Nature forces scientists, willing or not, to her truths.

AN EXEMPLARY SAGA OF SCIENCE

Several garden paths crisscross my field of research; here I retrace one such path.[18] It begins in Frankfurt with the work of Otto Stern, seventy-five years ago. The invention of the high speed vacuum pump had made it possible for him to undertake experiments using "molecular rays," now called "beams." These are tenuous, ribbonlike streams of molecules traveling in a vacuum at sufficiently low pressures to prevent disruption of the beams by collisions with background gas. The most celebrated of Stern's experiments using these beams was devised to test a curious prediction of the early form of quantum mechanics proposed by Niels Bohr. His atomic model postulated that an electron circulated around the nucleus only in certain definite orbits, whereas the classical mechanics of Newton imposed no such restriction. Stern's experiment focused on that key difference.

His simple apparatus was set up inside an evacuated glass tube, about the size of a quart jar. Silver atoms evaporated from a heated wire passed through a slit which collimated them into a narrow beam (only 0.1 mm wide, about the breadth of a human hair). The beam then passed between the poles of a small magnet and deposited its silver atoms on a glass plate. Stern's magnet was special: one pole came to a sharp edge, like the roof of a house; the opposite pole had a wide groove, like a trench. The magnetic field therefore was much stronger near the sharp pole, weaker near the grooved pole.

According to the Bohr model, the orbital motion of its outer electron makes a silver atom act like a tiny bar magnet. Furthermore, the model predicted that the atomic magnets could point only in either of two directions, "up or down," say, when the atoms interact with an external field, like that of Stern's magnet. Consequently, as indicated in FIGURE 1, atoms with one of these two allowed orientations would move towards the strong field of the

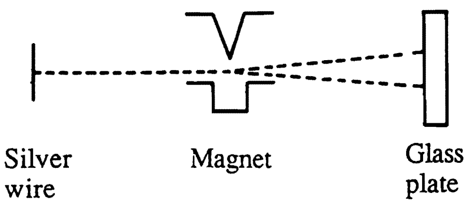

FIGURE 1 Stern's experiment: a beam of silver atoms splits into two on traversing a magnetic field, revealing "space quantization."

sharp pole, the other towards the weak field of the grooved pole: the beam would split into two components. In contrast, if Newton's mechanics were applicable to atoms as it is to planets, the atomic magnets could have any orientation in space: in passing through Stern's magnet, the beam would not split but merely broaden.

The experiment showed unequivocally that the beam split in two. This discovery, revealing the existence of what is now called "space quantization," was shocking to physicists of the day. It provided one of the most compelling items of evidence that a new mechanics was required to describe the atomic world. Two aspects are especially pertinent here. First, Stern himself did not want to accept the quantum picture; he hoped and expected that his experiment would support a Newtonian description of atoms. Second, the atomic magnetism demonstrated by Stern's experiment actually does not come from orbital electronic motion but from a different intrinsic property, called "spin," not discovered until a few years later. The Bohr model was soon discarded; it was seen to have merely simulated, in a limited way, some features of a far more comprehensive quantum theory. I note these aspects because they so clearly show how myopic is the view of cultural constructivists. In its historical context, Stern's experiment gave an "antisocial" result. Other experiments revealed the Bohr model was not correct; yet it was not "fiction" but rather scaffolding for the emergent quantum theory.

Descendants of Stern's beam technique and his concept of sorting quantum states are legion. The prototypes for nuclear magnetic resonance (NMR), radioastronomy, and the laser all derived from space quantization. NMR spectroscopy, first developed at Columbia University by Isidor Rabi in the late 1930s, deals with the orientation of nuclear magnets or spins in an external field. FIGURE 2 indicates the key aspects. For the different orientations, the energy of interaction of the nuclear spin with the field differs slightly. The higher energy state corresponds to an unfavorable orientation, the lower energy to favorable orientation. By means of radio waves of an appropriate "resonant" frequency, the nuclear spin can be induced to change its orientation, or "flip." However, it was not obvious that the minute nucleus, with dimensions about 100,000-fold smaller than the atomic electron distribution, would interact appreciably with the electrons. If not, the different nuclear spin orientations (favorable: "up" or unfavorable: "down") would remain equally probable even when subjected to an external magnetic field. There would then be no net absorption of resonant radio waves, since spin flips induced by the radiation are equally likely up or down. Net absorption can only occur if interactions permit the populations of the spin orientation states to be unequal.

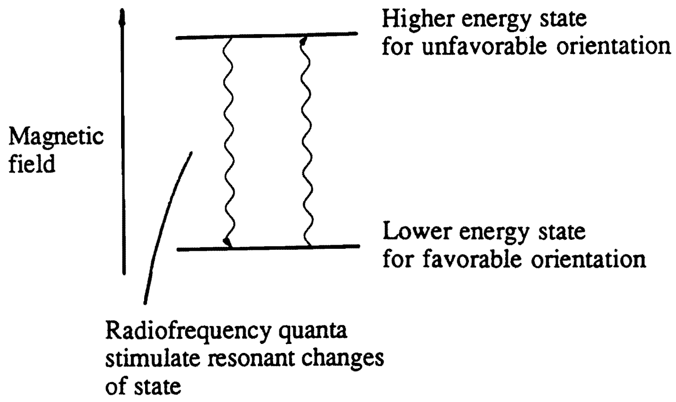

FIGURE 2 Rabi's experiment: transitions between energy levels, corresponding to different spin orientations, are induced by absorption or emission of quanta.

Rabi devised an elegant way to use atomic beams to escape this constraint. In an evacuated chamber, he introduced two magnets like Stern's, but with their fields in opposite directions. A beam of atoms traversing the first field (denoted A) is split into its nuclear spin components, but on passing through the second field (denoted B) these are recombined. Between these magnets, which act like diverging and converging lenses, Rabi introduced a third magnet (the C-field). This had flat pole pieces, so had no lens action, but served to define the "up" and "down" directions. Since atoms in the beam experience virtually no collisions, the populations of the component spin orientation states remain equal. Also, radio waves in the C-field region will at resonance flip equal numbers of spins up or down. But now any spin changing its orientation after the A-field will not be refocused in the B-field. That enabled Rabi to detect which radio frequencies produced resonances. He thus created a versatile new spectroscopic method with extremely high resolving power. His work provided a wealth of information about nuclear structure and led to many other fruitful developments.

The scope of NMR has expanded vastly since 1945, when resonances were first detected in liquids and solids, at Harvard by Edward Purcell and at Stanford by Felix Bloch and their coworkers. In these prototype experiments, the key discovery was that the populations of the "up" and "down" nuclear spin orientations in a magnetic field (C-field) become unequal by virtue of intra- and intermolecular interactions (so Rabi's A- and B-fields are not needed). Over the intervening decades, many sophisticated variants have been devised, with myriad applications. Now NMR spectra are routinely used to determine detailed structural features of proteins containing thousands of atoms. For instance, that was how the missing methyl group in the defective switch on the Y chromosome was detected.[19] Another marvelous offspring is magnetic resonance imaging, which provides far higher resolution than x-rays. It is applicable also to soft tissues such as the brain; we can now literally catch sight of glimmering thoughts.

Radioastronomy vastly extended what we can see of the heavens. The prototype experiment, conducted at Harvard by Purcell in 1951, detected radio frequency emission from the spin flip of the nucleus of a hydrogen atom, subject to the magnetic field generated by orbital motion of the atom's lone electron. Hydrogen is by far the most abundant element in the universe, and the ability to map its distribution soon revealed unsuspected aspects of the structure of galaxies. Kindred techniques employing radio frequency and microwave spectroscopy also revealed a remarkable variety of molecules in interstellar clouds, products of previously unsuspected galaxies of chemical reactions.

Beyond leading to ways to probe nuclei, proteins, and galaxies, the path stemming from Otto Stern even brought forth a new form of light itself: laser light. The name is an acronym for light amplified by stimulated emission of radiation. The prototype experiment, done at Columbia University in 1955 by Charles Townes and his students, employed a beam of ammonia molecules subjected to an electric field which acted as a state-selection device quite analogous to Stern's magnet. The device selected an energetically unfavorable molecular state. When illuminated with microwaves, the molecule reverted to the energetically favorable state, emitting the excess energy as radiation. Unlike ordinary light, this emission has a special property, called "coherence"; the difference is analogous to that between a meandering crowd of people and a marching band. Thus was born molecular amplifiers and oscillators and other wonders of quantum electronics.[20] Laser light now performs eye surgery, reads music or data from compact disks, and scans bar codes on grocery packages or DNA base pairs in the human genome.

As Stern was a physical chemist, he would be pleased that his beam techniques, augmented both by magnetic and electric resonance spectroscopy and by lasers, have also evolved powerful tools for study of molecular structure and reactivity. In my own work, the basic method simply involves crossing two molecular beams in a vacuum and detecting the products in free flight, before subsequent collisions degrade the information they carry about the intimate dynamics of the reactive encounter. This method, applied and refined in many laboratories over more than thirty years, has enabled the forces involved in making and breaking chemical bonds to be resolved and related to the electronic structure of the reactant molecules.

From this point, I want to trace a trail that backtracks from Stern's path. Usually, an atomic or molecular beam comes from a small source chamber mounted within a vacuum apparatus. Stern had stressed that the pressure in the source chamber should be kept low enough so that the atoms or molecules, as they emerge from the exit orifice, do not collide with each other. The emergent beam then provides a true random sample of the gas within the source, undistorted by collisions in the exit orifice. Of course, this canonical ideal was blatantly violated by chemists who wanted to study reactions in crossed beams. Such experiments desperately needed intensity, so much higher source pressures were used. Collisions within the exit orifice then produce supersonic flow. This has advantageous properties. In addition to high intensity, supersonic beams have narrow distributions in both direction and

molecular speeds. Under suitable conditions, the rotational and vibrational motions of the beam molecules can also be markedly reduced, in effect producing a very low internal temperature.

These properties of supersonic beams, all resulting from collisions as molecules crowd out the exit aperture, are readily understood by anyone who has attended a Saturday morning sale at a department store such as Filene's in Boston. Typically, a dense crowd gathers (like the high-pressure gas within the beam source). When the doors are thrown open and the crowd rushes in, collisions induce everybody to flow in the same direction with the same speed, whether they want to or not. Moreover, if some customers are excited at the prospect of a bargain and therefore leap about or turn handstands (like vibrating or rotating molecules), they suffer more frequent and harder collisions—even black eyes or bloody noses. Thereby such lively customers are calmed down (to low effective temperatures).

The drastic cooling that occurs in supersonic beams has proved extremely useful. In particular, it led to the discovery a few years ago of a new form of elemental carbon.[21] The molecules have sixty carbon atoms, arrayed in linked hexagons and pentagons in the same highly symmetrical pattern as a soccer ball, and whimsically named "Buckyball" to celebrate the architectural resemblance to Buckminster Fuller's geodesic domes. It is striking that the study that led to Buckyball was motivated by interstellar spectra. The question had been raised whether a series of absorption lines, long unidentified, might arise from clusters of carbon atoms. That seems not to be the case. Ironically, however, it was eventually shown that Buckyball and kindred molecules can be extracted in quantity from soot. For synthetic chemists, this has opened up a huge realm of potential molecular structures, built with a form of carbon that has sixty valences rather than just four. By looking at the heavens, scientists came to find, in ashes that had lain under the feet of ancestral cavemen, a Cinderella-like molecule.

Our path next pauses at a computer screen.[22] Three years ago a graduate student at the University of California at San Francisco was trying to see if he could find or design a molecule that would inactivate an enzyme that is crucial for replication of the AIDS virus. The inactivating molecule needs to have the right size and shape to fit into a cleft in the enzyme. The molecule also needs to present a water-repellent torso, since the cleft is hydrophobic. A friend of the student, listening to him lament about what he tried that did not fit, jokingly suggested he try Buckyball. He went back to the computer and found it was just right. Soon a chemist at the University of California at Santa Barbara synthesized a derivative of carbon-sixty which has a pair of wings that make the molecule water soluble despite its hydrophobic torso. Physiologists at Emory University in Georgia then found that, at least in a test tube, this Buckyball derivative does indeed totally inactivate the enzyme that governs replication of the AIDS virus.

This is still a long way from having an actual AIDS drug that can function in living cells. However, the path from Stern's atomic magnets to the AIDS virus, like many others, serves to emphasize that research on fundamental questions inevitably creates a host of unforeseeable opportunities. No funding agency would find plausible a research proposal requesting support of work on supersonic beams or interstellar spectra as an approach to AIDS. But many such historical paths can be traced that celebrate hybridizing discoveries from seemingly unrelated patches of scientific gardens.

SCIENCE AMONG THE LIBERAL ARTS

In *As You Like It*, set in an imaginary garden, Shakespeare said: "Sweet are the uses of adversity, which, like the toad, ugly and venomous, wears yet a precious jewel in his head." The fruits and flowers of science and rationalism are, I believe, hardy enough to withstand even venomous critiques. Provided we gardeners respond well, the critiques can help us learn how to nurture better our precious flora. Like our gardens, the newly luxuriant growth of "science criticism" in academic fields will be subject to the scrutiny of a coming generation of scholars. With that in mind, I conclude with three comments emphasizing why and how we need to cultivate common ground, shared by science and the liberal arts.

1. The masterworks of natural science and human arts alike testify to the marvelous creative capacities of mankind. Wherever in the world these emerged, they now are a rich legacy cherished by all cultures. This should be a powerful force for amity. Forty years ago, as a beginning graduate student, I heard this theme sounded by Rabi in a fervent lecture to the Harvard physics department:

> How can we hope to obtain wisdom, the wisdom which is meaningful in our own time? [The wisdom of] balanced judgment based on . . . a well-stored mind and feeling heart as expressed in word and action. . . . We certainly cannot attain it as long as the two great branches of human knowledge, the sciences and the humanities, remain separate and even warring disciplines. . . .
>
> To my mind, the value of science or [the humanities] lies not in the subject matter alone, or even in greater part. It lies chiefly in the spirit and living tradition in which these [different] disciplines are pursued. . . . Our problem is to blend these two traditions. . . . The greatest difficulty which stands in the way . . . [is] communication. The nonscientist cannot listen to the scientist with pleasure and understanding.
>
> Only by the fusion of science and the humanities can we hope to reach the wisdom appropriate to our day and generation. The scientists must learn to teach science in the spirit of wisdom, and in the light of the history of human thought and human effort, rather than as the geography of a universe uninhabited by mankind. Our colleagues in the nonscientific faculties must understand that if their teachings ignore the great scientific tradition and its accomplishments, however eloquent and elegant in their words, they will lose meaning for this generation and be barren of fruit. Only with a unified effort . . . can we hope to succeed in discovering a community of thought, which can lead us out of the darkness, and the confusion, which oppress all mankind.[23]

Rabi later discussed these concerns with C. P. Snow, who developed them further in his famous *Two Cultures.*

Today, the cultural gulf seems wider and more ominous. The recently proposed new national standards for teaching American history are blatant evidence.[24] From a process extending over three years and involving many his-

torians, there emerged a 250-page document describing the new curriculum for grades 5–12. It makes no mention of any scientific discovery or any scientist, not even Benjamin Franklin.

2. Yet there is also much to hearten both scientists and humanists responsive to Rabi's appeal. Many efforts are now under way to foster major reforms in science education at all levels. The past forty years have in fact produced an outpouring of articles, books, films, and TV programs that make science accessible to a wide public. Most large cities now have thriving science museums; for instance, last year the Boston Museum of Science drew nearly 1.7 million visitors (compared with 2.2 million for a typical Red Sox season). The Internet soon will greatly enhance such resources.

Excellent science writing in a humanistic mode is now abundant. Much of this stems from the history of science, approaching full bloom as an academic discipline (even if often ignored by other historians). Much also comes directly from scientists writing of "human thoughts and effort," exemplified by Lewis Thomas, Victor Weisskopf, Philip and Phylis Morrison, Gerald Holton, Freeman Dyson, Jeremy Bernstein, Carl Sagan, Jared Diamond, James Trefil, Roald Hoffmann, and many others.[25] Another genre effective in conveying both specific and cultural aspects is fiction incorporating genuine science (in contrast to science fiction);[26] a fine example is Carl Djerrasi's recent novel, *The Bourbaki Gambit.*

A liberal arts education worthy of the tradition surely must aim to integrate science into our general culture. But we cannot expect to accomplish much if we continue to confine science to separate courses. Even a "physics for poets" course reinforces the prevalent view that science belongs solely to its professionals. There are abundant opportunities to include some science in many other subjects—and vice versa! Often such items, used to broaden perspectives, take the form of parables. Here are a few examples, appropriate for various courses.

Economics

In 1880, aluminum metal was more precious than gold. Although aluminum ores are plentiful, the metal is tightly bound to oxygen, and no cheap means had yet been found to free it. Consequently, the Washington Monument is capped with a small pyramid of aluminum; The Danish King Christian X wore a crown of aluminum; and at dinner parties of Napoleon III, plates of gold were placed before ordinary guests, an aluminum plate before the guest of honor. In a chemistry class at Oberlin College, Charles Hall heard his professor assert that "whoever frees aluminum from its oxide, will make his fortune." Hall undertook a long series of experiments, working in a woodshed with a frying pan and jars borrowed from his mother's kitchen. By 1886, he found he could dissolve aluminum oxide in a molten mineral, install electrodes, and run electricity to free the metal.[27] (This is still the way the metal is obtained.) Within a few years a new industry had emerged and the price of aluminum metal had dropped to about fifty cents a pound. The price has remained fairly constant for the past century, but economists seem not to have proposed using aluminum as a monetary standard.

History

Polymer synthesis had a crucial role in enabling the United States to enter World War II.[28] The Japanese attack on Pearl Harbor on December 7, 1941, was much less disastrous than the fall of Singapore three months later. That deprived the United States and Britain of virtually their sole supply of rubber. As stated in a report by Bernard Baruch:

> Of all the critical and strategic materials, rubber presents the greatest threat to the success of the Allied cause. . . . If we fail to secure quickly a large new rubber supply, our war effort and our domestic economy both will collapse.[29]

This report launched a crash program to produce synthetic rubber, using a method developed and implemented in Germany. In effect, our enemy had provided the saving key. Some 50 plants were quickly built, enabling military action to start in late 1942. The Allied victory could not have been achieved without this enormous rubber project. However, for it to succeed on such an urgent time scale, we had to have a sufficient corps of polymer chemists and engineers. It was actually the pursuit of artificial silk started 15 years before and culminating in nylon that largely created those vital human resources.

Political Science

The eminent historian of science, I. Bernard Cohen, has just published a remarkable book, *Science and the Founding Fathers.* This traces the role of science in the political thought of Franklin, Jefferson, Adams, and Madison, an aspect "conspicuously absent from the usual textbooks." Here I will mention just a bit about Franklin. As an American icon, he is aptly portrayed as wise, witty, and pragmatic in business and politics, but his scientific work is greatly undervalued. He is represented as a chubby, comic fellow flying a kite or a clever tinkerer coming up with useful devices, such as the lightning rod, bifocals, and an efficient stove. As Cohen emphasizes, in the early eighteenth century, electricity was a greater mystery than gravity had been a century earlier. Franklin, almost entirely self-educated and far from any center of learning, solved that mystery. His book, *Experiments and Observations on Electricity*, was a sensation in Europe: it went through five editions in English and was translated into French, German, and Italian. It was read not only by scholars but by the literate public, including the clergy and aristocracy. Many high honors were bestowed on Franklin, including election as a foreign associate of the French Academy; he was the first American elected and the only one for another century.

His scientific stature, comparable to Newton in his day or Einstein in ours, had a significant role in the success of the American Revolution. Franklin's arrival in Paris in 1776 coincided with the signing of a nonaggression pact, which specified that France not aid any rebellion in the British Colonies. His fame as the tamer of lightning helped him gain influence with the French court and immense popularity with the public. That accelerated and enlarged the vital flow of arms and funds supplied by the French to the American rebels. Indeed, Franklin's celebrity was like that of a rock star today; although T-shirts were not yet fashionable, his image appeared everywhere in Paris on medallions and banners, often with the motto *Eripuit celeo fulmen sceptrumque tyrannis* ("he snatched lightning from the sky and the scepter from tyrants"). Louis XVI became so annoyed by this veneration that he gave his favorite mistress a chamber pot with a Franklin medallion at the bottom of the bowl.

Mathematics

The account of Thomas Jefferson's science in Cohen's book offers several items that could provide an appealing and instructive context for standard topics. My favorite concerns Jefferson's mathematical skill. Among the extraordinary range of his intellectual interests, Jefferson ranked science as his "supreme delight." He especially esteemed Isaac Newton, studied avidly the *Principia*, and mastered geometry and calculus. When Jefferson undertook to design an improved plow, a key question was the optimum shape of the moldboard, the part that peels back and turns over the sod as the blade cuts through the soil. At first, he pursued this by trial and error, using only simple geometrical calculations. On consulting some mathematical friends, however, he realized that finding the optimum shape required a solution of a calculus problem. He was thus able to treat the plowing of earthly furrows by means of a mathematical tool that Newton had developed to analyze the orbits of heavenly bodies. Jefferson's moldboard design remained the standard for a century; it might open vistas for calculus students today.

3. A liberal arts education aims above all to instill the habit of self-generated questioning and adventurous thinking. In pursuit of that aim, as urged by Bronowski and Rabi, the humanities and sciences should be complementary. Each academic subculture deals with entirely different kinds of questions, develops very different criteria for evaluating answers, and evolves its own language. That handicaps interdisciplinary communication, but need not be allowed to engender disrespect. Science or any subculture can only treat questions amenable to its methods. We should strive for an inclusive intellectual society in which the whole can greatly exceed the sum of its parts.

In conclusion, I return to Peter Medawar, because he stated so well what I believe:

> I am a rationalist, but I'm usually reluctant to declare myself to be so because of the widespread misunderstanding or neglect of the distinction there must always be drawn in philosophic discussion between the sufficient and the necessary. I do not believe, indeed I deem it a comic blunder to believe, that the exercise of reason is *sufficient* to explain our condition and where necessary to remedy it. But I do believe that the exercise of reason is at all times unconditionally *necessary* and that we disregard it at our peril. I and my kind believe that the world can be made a better place to live in . . . believe, indeed, that it has already been made so by an endeavor in which, in spite of shortcomings which I do not conceal, natural science has played an important part. . . . To people of sanguine temperament, the thought that this is so is a source of strength and the energizing force of a just and honorable ambition. . . . The dismay that may be aroused by the inability of science to answer the ultimate first and last questions is really something for which ordinary people have long since worked out for themselves Voltaire's remedy: "We must cultivate our garden."[30]

NOTES

1 R. Seltzer, "New Television Series May Draw both Kudos and Arrows."
2 M. C. Seidel, "The Forgotten Science"; D. R. Herschbach, "On the Nobel Legacy."
3 F. Ashall, *Remarkable Discoveries*, pp. 137–151, 160–170.
4 Quoted in R. W. Clark, *Benjamin Franklin*, p. 89.
5 Personal communication from J. Folkman, derived from *The International Classification of Diseases*, 9th Revision, 1996.
6 Quoted in P. Medawar, *The Limits of Science*, p. 40.
7 H. Rosovsky, "Appearing for the Defense Once Again."
8 See, for example, D. W. Curtin, ed., *The Aesthetic Dimension of Science*; S. Chandrasekhar, *Truth and Beauty*; R. Hoffmann, *The Same and Not the Same.*
9 Quoted in M. Kundera, *The Art of the Novel*, p. 99.
10 T. S. Kuhn, *The Structure of Scientific Revolutions.*
11 M. Polanyi, *Personal Knowledge*; *The Tacit Dimension.*
12 S. Harding, *The Science Question in Feminism*; "Value-Free Research Is a Delusion."
13 Quoted in J. Mehra, *The Beat of a Different Drum: The Life and Science of Richard Feynman*, p. 599.
14 E. F. Keller, *Reflections on Gender and Science*; E. Martin, "The Egg and the Sperm: How Science Has Constructed a Romance Based on Stereotypical Male-Female Roles."
15 T. W. Sadler, *Langman's Medical Embryology.*
16 J. D. Wilson, "Sex Testing in International Athletics."
17 C. M. Haqq, C.-Y. King, E. Ukiyama, S. Falsafi, T. N. Haqq, P. K. Donahoe & M. A. Weiss, "Molecular Basis of Mammalian Sexual Determination."
18 D. R. Herschbach, "Molecular Dynamics of Elementary Chemical Reactions."
19 Haqq *et al.*, "Molecular Basis."
20 C. H. Townes, "Quantum Electronics, and Surprise in the Development of Technology."
21 R. F. Curl & R. E. Smalley, "Fullerenes"; H. W. Kroto, "C_{60}: The Celestial Sphere That Fell to Earth."
22 R. Baum, "Fullerene Bioactivity."
23 Quoted in J. S. Rigden, *Rabi, Scientist and Citizen*, pp. 256–257.
24 R. L. Park, "The Danger of Voodoo Science."
25 A sampling of recent vintage: Gerald Holton, *The Advancement of Science and Its Burdens*; Philip Morrison & Phylis Morrison, *The Ring of Truth*; James S. Trefil, *Meditations at Sunset*; C. Tanfold, *Ben Franklin Stilled the Waves*; R. Levi-Montalcini, *In Praise of Imperfection*; Victor Weisskopf, *The Joy of Insight*; S. J. Gould, *Wonderful Life*; B. Hölldobler and E. O. Wilson, *Journey to the Ants*; P. Ball, *Designing the Molecular World.*
26 L. Herschbach, "'True Clinical Fictions': Medical and Literary Narratives from the Civil War Hospital."
27 N. C. Craig, "Charles Martin Hall—The Young Man, His Mentor, and His Metal."
28 H. F. Mark, *Giant Molecules.*
29 Quoted in H.F. Mark, *Giant Molecules*, p. 130.
30 Peter Medawar, *The Limits of Science.*, pp. 98–99.

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