Reflections, Reminiscences, and Ramblings on the Theme: Memory and Creativity

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A man hath sapiences thre
Memorie, engin and intellect also

Chaucer

When, a little over a year ago Professor McConkey asked me to lecture in this series, I knew I had to do it. Chances to share insights obtained from a career in science with a general audience in a formal setting do not occur often. Doubts came later, especially when an article headed 'Area celebs to lecture on memory,' and leading off with 'So what inspires some of the best and brightest[†] in Ithaca: How do they get their ideas? What makes their minds tick?' appeared in the Ithaca Journal. I do hope you have not come to hear my mind ticking (down?).

Doubts persisted. Why I was chosen? You may be curious to know. So am I. At one stage I thought it was because Jim McConkey was present at my daughter's wedding where I recited some poems from memory, but he tells me that he was unavoidably delayed, and missed my performance. So the question remains a mystery. Ultimately, though, and like many professors, I am better at stilling doubts about being honored than at overlooking being overlooked.

[†] The book title, 'The Best and the Brightest,' from which the current wide use of this formula seems to have sprung, has always struck me as metrically deficient. When I mentioned this to my great friend Scott Elledge, Goldwin Smith Professor of English, emeritus, he immediately retrieved a metrically sound quote from Kipling,

Very great our loss and grievous—
So our best and brightest leave us,

which in its context (the poem 'Files') makes clear that this year's best and brightest are next year's unknowns. So perhaps with a literate memory as guide the phrase fits uncannily well.

What am I going to tell you? That creativity in the mathematical sciences is both very much easier and very much harder than in other human endeavors, similar in some ways and very different in others, and that memory is as essential to creativity here as elsewhere. Much will be based on personal experience, and anecdotal rather than researched. On the other hand, as my wife will be the last to agree, when I tell stories it's because I think there is something general to be learned from them. Along the way, I hope to convey something of the nature of the scientific enterprise, particularly as it is carried out by theoretical physicists.

What is physics? 'Physics is a body of knowledge and a point of view. Both have grown out of the astonishing discovery in seventeenth century Europe that the observed workings of inanimate nature, from how the planets move to how a prism makes a rainbow, can be accurately summarized in mathematical terms. Why the world is thus regulated and why we have evolved to a point a little beyond cats from which we can perceive these regularities are questions for which science has no answers.†

'That mathematical relationships ('Laws') do exist is demonstrably true. The physical laws that have been discovered—by a mixture of observation, intuition, and a desire for a concise and therefore in some sense beautiful description—do not merely organize experience, they organize it in a manner that encourages disprovable predictions. The wave theory of light predicted a bright spot in the center of the shadow cast by a circular screen, a result so apparently absurd that it made believers of disbelievers when it was found. In physics, the search for unifying laws is a continuing quest. Great unifications have, however, occurred rarely; when they do they become part of the physicist's general knowledge and confer well-deserved immortality on their discoverers. The daily work of most theoretical physicists is more mundane. Some, working in areas where the laws are not well-formulated, have the satisfaction of constructing bits and pieces of mathematical

† If you are interested in reading about attempts at answers, the key-words *Anthropic Principle* will get you started, at your own risk, in a good library.

structure that explain on general grounds why observed phenomena occur and unobserved do not, building blocks for greater constructions to come. Others are able to understand how an apparently bizarre observation is a consequence of accepted theory, or—and this is a great joy—of predicting quantitative relations between measurements, or phenomena few would have anticipated. When there are disagreements it is often unclear whether the observations, the mathematics, or both are at fault. The resolution of conflicts is emotional and often heated. More than in most fields of scholarship, though, when the dust settles, it settles for good. This suggests that the physical study of nature is an act of uncovering a hidden structure. That we are inextricably part of the structure makes its study all the more fascinating.'†

As you can see, I agree with Einstein that 'the eternal mystery of the universe is its comprehensibility.' This comprehensibility, even with its potential for misuse, is surely a piece of extraordinary good fortune. It is worth remembering, though, that essentially all of human evolution took place before the scientific age. This is just as well, since many if not most of the problems an ordinary person encounters in an ordinary day are better dealt with by using the human qualities of intuition and judgement, guided by a sense of the past, than by some kind of coldly 'scientific' analysis. The advantage that a knowledge of science confers is help in identifying (using intuition and memory) problems which will yield to precise analysis.

Since I want to talk about a little more than just physics I should also tell you what the words mathematical sciences mean to me. I once heard the critic I. A. Richards say something I have already echoed: Science is an organization of experience with a view to prediction. Let us agree that a mathematical science is one in which the experience to be organized has self-evident mathematical regularities. This more or less restricts me to physics, chemistry, and closely related sciences and technologies. As a simple example

† This and the quote on the following page are from *Reasoning about luck: probability and its uses in physics*, V. A., Cambridge University Press, to appear in 1996.

of self-evident mathematical regularities, 'Consider the oxides of sulfur. There are two of them, both gases at ordinary temperatures and pressures, and neither very pleasant to breathe; both implicated in acid rain, where they do not belong, and important in chemical engineering, where they do. We can learn something from them. They contain, respectively, 50.05 % and 40.04 % by weight of sulfur: the ratios of sulfur to oxygen in these compounds are $f_1 = (50.05/49.95)$ and $f_2 = (40.04/59.96)$. Amounts of the two compounds containing a given weight of oxygen thus contain sulfur in the ratio f_1/f_2. . . Work out this ratio, and you will find to two decimals, which is the accuracy of the data, the number 1.50. In short, when sulfur combines with oxygen it can do so in two ways: if two parts of sulfur combine with a certain amount of oxygen to make one of the oxides, three parts of sulfur combine with the same amount of oxygen to make the second one. The emergence of these small integers from genuinely uninspiring raw data is a strong indication that some simple principle is at work.† '

The stage is now set for some remarks on the very challenging theme that is the title of this innovative course. Set rather too sparsely, you may protest. Indeed, some of what I shall have to say surely applies to sciences less narrowly circumscribed, and some to creative work in general. But, you are as well qualified as I am to make justified extrapolations, and I am freed from having to talk about things like scientific methodology, inference, and validation which, when the 'dust' I spoke about earlier settles, play little role in my business—where the phenomena to be understood, predicted, interrelated, have a self-evident mathematical structure.‡

My epigraph, from the second nun's Canterbury tale, rather nicely attributes three qualities to the mind; memory, ingenuity which for the present purposes we can take to be

† No straightforward manipulation of equally uninspiring, but equally important, raw data in economics—the number of car-loadings of cheese exported from Denmark in different months, for example—yields ratios of small integers, which indicates that any simple underlying mathematical principles in the 'dismal science' are well hidden. [See Chapter 11 ('Chaos')for a modern perspective on how such things can happen.]

‡ A good more general discussion of the sreative process in science is to be found in *Induction and Intuition in Scientific Thought* by P. B. Medawar, American Philosophical Society, 1969.

synonymous with creativity, and the ability to reason. The ordering is also good: memory at the root of everything. Indeed, without memory there can be no scientific creativity. Isaac Newton wrote to Robert Hooke, 'If I have seen further it is by standing on the shoulders of Giants.' The memory brought to bear on a scientific question need not be encyclopedic. But, even if truly creative scientists are likely to be quite selective about keeping up with the froth of intellectual fashion, every such person I have known has had a large number of facts and their consequences stored in the memory. The first moment of creativity usually comes in the form of an analogy with something previously understood. This has always been my experience; and I shall describe one such happy occasion soon. The first moment of understanding other people's creativity often comes in a similar way. After struggling for days in confusion and frustration with a paper reporting progress I needed to understand, I have on more than one occasion said to myself with some annoyance, 'If that's what it is why didn't they say so in the first place?' What has happened in this 'aha' moment—a minor version of something Poincaré† describes so well—is that the problem and the method of solution have been viewed from one angle and then another until there is a click as it fits into something previously understood. Preparing material for teaching can lead to similar moments. Needing to explain something called Liouville's theorem to a class in which some members were having difficulty thinking abstractly, so that the standard avenue to the theorem—Hamilton's formulation of mechanics—would quite possibly not have been understood, I suddenly realized that a proof could be constructed using elements the students had to be more comfortable with. For all I know, 'my' proof is in books unknown to me, but this was a moment where 'memorie' and 'engin' came together, the first being needed for the second. I was pleased enough with the proof to show it to a colleague who said: 'One giant leap backward for mankind.' Creative teaching is a hard and thankless business!

The final working out of a creative thought requires good training and technique:

† See *The anatomy of memory*, James McConkey, ed., Oxford University Press 1996.

'intellect,' I suppose. This is not to suggest that a single 'aha' ends the truly creative part of scientific discovery. Einstein describes as 'the happiest thought of my life' his realization that 'if a person falls freely he will not feel his own weight.'† It took seven more years of false starts and other creative insights before he reached his geometrical theory of gravitation. Over this period, though, the three-fold division is not far fetched, and the memory of such things as Newtonian Gravity and Riemannian geometry—the latter brought to Einstein's attention by his friend Grossmann—was crucial.

So what then is different about creativity in the mathematical sciences, if a fourteenth century quote—and, at that, a rendering into early English of a certainly much older thought—describes its structure? It is the fact that simple natural phenomena, being self-evidently mathematical, can be described in mathematical language, so that reasonable people can agree when something has been understood, and when a mistake has been made. Rather than talking in abstract, I shall tell you a story. Luckily, you have recently read an essay by Montaigne‡ explaining why it is not necessarily reprehensible to talk non-stop about one's self.

In the summer of 1962, six months after I came to Cornell, I was invited to spend a month at the Bell Labs. Summer at the Bell Labs in those days was the ultimate ivory tower and a paradise* for what was then called solid state physics, and is now more often referred to as condensed matter physics. During that month I learned from P. W. Anderson about a discussion earlier that summer between a Cambridge graduate student, Brian Josephson, and John Bardeen. [These will be just names to some of you, but they are famous names to condensed matter physicists: all have since won Nobel prizes, Bardeen his second; he already had one at the time for the transistor, the device which started the 'silicon age.'] The discussion was about a calculation done by Josephson early that year, predicting that

† See *Subtle is the Lord*, A. Pais, Oxford University Press, 1982.

‡ *ibid.*

* Proust, in the section of *Le Temps Retrouvé* you have been reading in translation, *ibid.*, writes: '. . . les vrais paradis sont les paradis qu'on a perdus.' The Bell Labs today is, alas, not what it used to be.

an electrical current could pass without resistance between two superconductors separated by a thin insulating layer. Bardeen had expressed the opinion, and somewhat later said in print, that the calculation was incorrect. The curious thing about this disagreement is that Josephson was using the BCS theory of superconductivity (developed by Bardeen, Cooper, and Schrieffer in 1957) which had finally and very beautifully explained the then 46 year old puzzle of how certain materials ('superconductors') conduct electricity without friction at low temperatures. Before your eyes glaze over, let me move from the details to the bigger picture. A young man is predicting a new and striking effect; his reasoning is being disputed by the most respected figure in the field.

Bardeen was my hero. Not only because I had studied the BCS theory but also because as a graduate student I had been asked to give a few seminars on the background to the subject, and for that purpose had read a long review article written by him just before the new theory appeared. That review made it clear that he had followed with great care and tenacity all the clues that experimental research had been revealing. His own reasoning was very hard to follow, and some of it, in hindsight, clearly wrong. But it was wrong in a deep way: his wrong arguments had the seeds of how matters did in fact work out when the pieces were put together correctly. So, when I got back to Cornell, I said very grandly to my first graduate student, Alexis Baratoff, 'Bardeen is having a disagreement with some Englishman. Bardeen is always right. Let's find out why.'

It took us most of the fall term to acquire the necessary background. Meanwhile, Josephson's paper appeared. Yet, somehow, it was difficult for us to decide one way or the other about Bardeen's objection, because the key question of how far from the surface of a superconductor the order special to superconductivity extended was buried in the formulas. In the midst of this confusion, it occurred to me that it might be useful to translate Josephson's steps into another (equivalent) mathematical language—developed by L. P. Gor'kov and other Russian physicists—which I *remembered* as allowing for an easier visualization of spatial dependences. No sooner was this done than it became clear

to us that Josephson was right!

It was not clear what general interest there might be in our epiphany, so we delayed submitting it for publication. Meanwhile early in 1963, I privately circulated the calculation which earned me letters from Bardeen (saying that our calculation was elegant but wrong) and Anderson (saying that he had always believed Josephson). Some weeks later, we decided that since Josephson had not calculated the temperature dependence of his current—which would be a useful diagnostic prediction—we should do that, thereby making our work more clearly new and interesting.

At this point my story takes an interesting turn. Our work appeared in the June 1 issue of the journal Physical Review Letters. It contained a calculational error, so that the published curves were not a correct representation of what the theory actually predicts! Shortly thereafter I received an extremely charming letter from a French physicist, P. G. de Gennes, in which he said that he liked our work very much, but that we had gone astray at the very end. He was right, so we corrected the calculation and submitted an erratum—which appeared in the July 15 issue of the same journal—in which we acknowledged our debt to de Gennes. [Incidentally, de Gennes has since also won the Nobel prize.]

In August (1963) there was a conference at Colgate University here in Upstate New York. All of the players in this game were there. By this time the Josephson current had been detected, by Rowell and Anderson at the Bell Labs, and Bardeen had come around to agreeing that the calculation was correct, but there had been no prior report of measurements of the temperature dependence. At the conference I met an experimental physicist from the GE laboratories in Schenectady, Milan Fiske. Quite unknown to me, he had been measuring precisely what we were claiming to predict. I do not know whether he had started his work before or after our letter appeared, but he told me that he was taking data in the month of June, during which time it became clear to him that there was a discrepancy between what he was seeing and our published curves. Since it was apparently going to be necessary for him to report a failure of the theory, he made new and careful

measurements which were just completed when the erratum came out. His results, taken in ignorance of our mistake agreed with the corrected calculation.

It is worth reflecting on this episode, because it brings out the fact that in the mathematical sciences one is engaged in a kind of archaeology; an uncovering of hidden artifacts. This wonderfully constrains the creative imagination, as it is possible to be clearly wrong. In my story, the error was of a rather simple kind: 'memorie' and 'engin' worked well; but, as with W. S. Gilbert's little tomtit on a tree by a river, there was a—luckily less fatal—'weakness of intellect.'

One word of caution. My story may have given the impression that in physics theory leads experiment. This is very far from being the case. Nature is at root mathematical, but her ways are with very rare exceptions more inventive than our most imaginative dreams.

If I have convinced you that there is something different about creativity in the mathematical sciences, does this mean that there is some great cultural abyss between science and other human endeavors? It is true that one cannot blur the distinction between scientific and other sorts of creativity. Poems and paintings about physics, insofar as they are supposed to be physics, are certain to be bad physics and likely to be bad poetry and art. On the other hand, from my perspective as a scientist, I don't see any unbridgeable chasm. I suppose that like many physicists, I have a tendency to be arrogant about this. I once heard Richard Feynman, perhaps the most creative scientist of the latter half of our century, say something like: 'I met a painter once, and I made a deal with him. You teach me painting; I'll teach you physics. I learned how to paint. He didn't learn physics. I don't know why.' Now, I've never seen any of Feynman's paintings, but there are examples enough of scientists as pretty good sculptors or poets or musicians to suggest that C. P. Snow in *The Two Cultures* was talking more about high table conversation in post World War II Cambridge than about a general phenomenon. Crossings in the other direction are rarer; the age of the gentleman scientist is over. It is close to impossible to dabble in science; it is too big and intense an enterprise.

Does this mean that non-scientists have to be totally in the dark about the excitement of my calling? There are books without equations which sell in great numbers, so they must be filling a need. Most such books talk about the most recent and speculative ideas. You have to tell me what they communicate. Typically, I find that they cannot be understood. Feynman, somewhere, complains about this, and in his own semi-popular writings goes to considerable pains to give complete and correct explanations. The difficulty is that for even moderately deep scientific understanding a different language is needed, and this has to be studied.† Now it takes at least two years, and a lot of reading to acquire a foreign language, and few people apart from scientists put that sort of effort into studying science. And I am sure it is yet more complicated. Some predisposition, as for music, is required. On the other hand, though I am unmusical I have been taught to play the piano a little. But here again there are differences. Although it takes study and thought to appreciate music deeply, one can enjoy it at various levels. As a result of Professor Austin's kind private instruction, I have come around to Mark Twain's opinion of Wagner's music: it *is* better than it sounds.‡ Even though it is highly doubtful that I will ever play Liszt, I am immensely enjoying my current bed time reading—Charles Rosen's *The Romantic Generation*—and can appreciate Schumann's audacity and intention in his Abegg Variations of tying two notes together and putting a stress mark and a pedal indication on the second. Significantly, though, one can get something from this book without studying the earlier *The Classical Style*, whereas writings in physics are sequential and impenetrable without background knowledge.

An achievable educational goal may be to try to communicate the excitement of some corner of physics to the interested non-specialist. When physics is taught seriously it is usually taught to non-scientists in the same way as it is to budding professionals: the first

† Galileo Galilei (1564-1642), arguably the first modern physicist, said about the 'book' of Nature: . . . it cannot be read until we have learned the language and become familiar with the characters in which it is written. It is written in mathematical language.'

‡ And on a completely different subject,when I had minor surgery last summer I was glad that it was not done with original instruments.

two years are a preparation for a (in this case non-existent) second two. For what I am talking about, the answer may be to go further into special topics, and with mathematics so that it is not a sequence of fairy tales. Various attempts in this direction are made in the physics department at Cornell. My own attempt is to be found in my book, which I have already shamelessly brought to your attention.

Does it matter that many people in a world in which science as culprit or as savior is *the* force are truly ignorant of it? As I said before, most of human evolution took place before the scientific revolution, and one can hope that evolution has favored common sense. Common sense requires looking at evidence unflinchingly, and that is ultimately the scientific way. [Alas, I seem to be giving the argument for jury trials. . .] On balance, I think it cannot hurt for everyone to know a little more about science. Those who know about the size of molecules will not try to keep an opened bottle of champagne fresh by putting aluminum foil around its neck, though for all I know those who do just that may be trying to keep and succeeding in keeping flies out.

Obviously the time has come to end these ramblings. I would like to do this by addressing the undergraduates who, amazingly, are receiving academic credit for listening to me and who deserve some homework. First, some avuncular advice: The life of the mind is a wonderful thing; enjoy it while you can; take the initiative to learn widely as well as deeply. Also: Denigrating memory has gone too far.† Some may tell you that you can find out everything you need by logging on to the internet, and surfing the world wide web. Don't count on it. And what about your own home page: is that to be a compilation of everyone else's home pages? I will assert that who you are is determined by what you have in your very own and not your computer's memory. If there is a poem that has caught your fancy, memorize it. If not, find one and memorize it. It will serve you, as will logical thought, in really tough times.

† See the inspiring essay by Clara Claiborne Park in your reading, *ibid.*