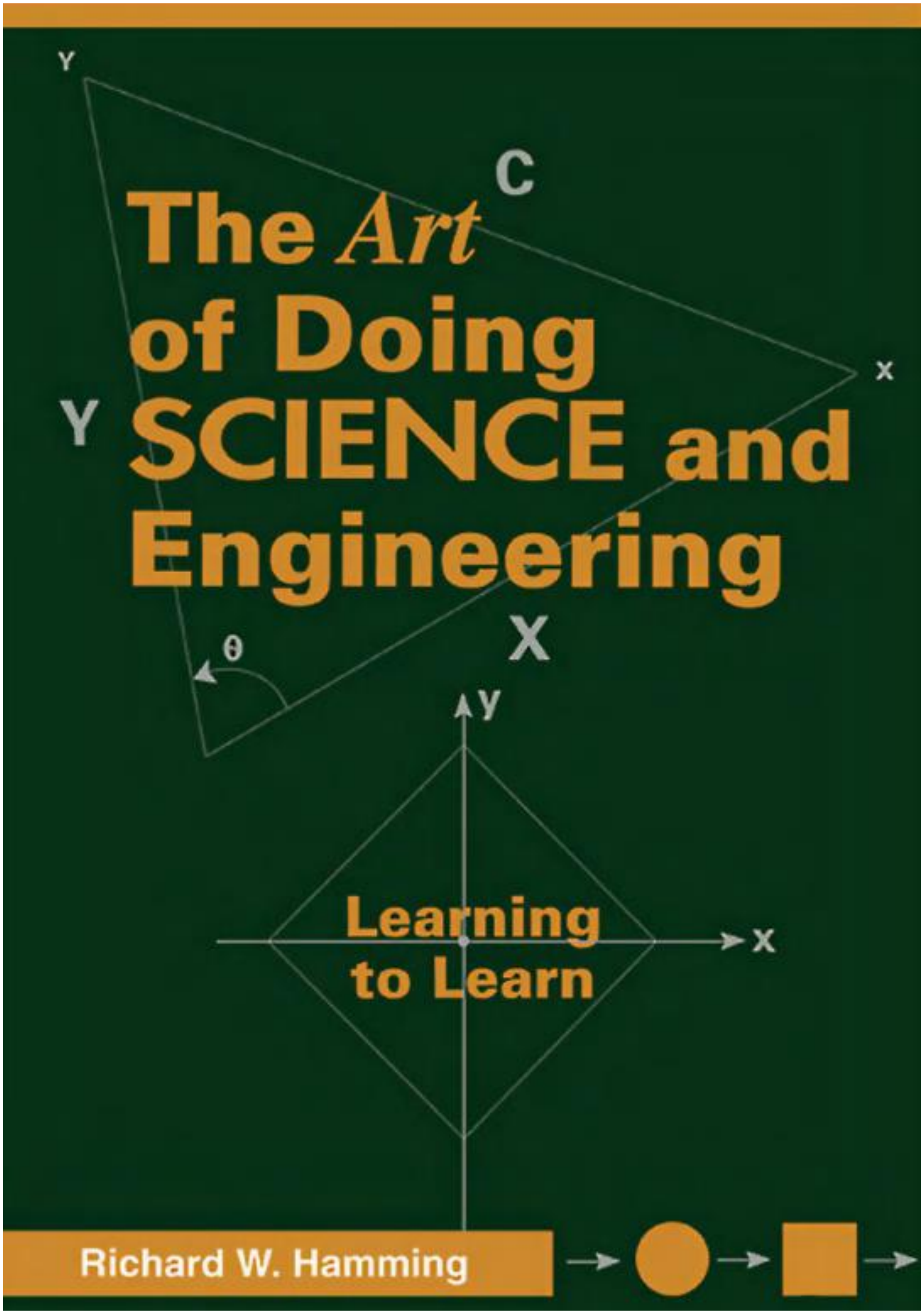
The Art of Doing Science and Engineering: Learning to Learn

By Richard Hamming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Summary

1. After more thought, I decided that since I was trying to teach "style" of thinking in science and engineering, and "style" is an art, I should, therefore, copy the methods of teaching used for the other arts – once the fundamentals have been learned. How to be a great painter cannot be taught in words; one learns by trying many different approaches that seem to surround the subject. Art teachers usually let the advanced student paint, and then make suggestions on how they would have done it, or what might also be tried, more or less as the points arise in the student's head – which is where the learning is supposed to occur! In this series of lectures, I try to communicate to students what cannot be said in words – the essence of style in science and engineering. I have adopted a loose organization with some repetition since this often occurs in the lectures. There are, therefore, digressions and stories – with some told in two different places – all in the somewhat rambling, informal style typical of lectures. I have used the "story" approach, often emphasizing the initial part of the discovery, because I firmly believe in Pasteur's remark, "Luck favors the prepared mind." In this way, I can illustrate how the individual's preparation before encountering the problem can often lead to recognition, formulation, and solution. Great results in science and engineering are "bunched" in the same person too often for success to be a matter of random luck. Teachers should prepare the student for the student's future, not for the teacher's past…Therefore, style of thinking is the center of this course. The subtitle of the book, Learning to Learn, is the main solution I offer to help students cope with the rapid changes they will have to endure in their fields. The course centers around how to look at and think about knowledge, and it supplies some historical perspective that might be useful. This course is mainly personal experiences I have had and digested, at least to some extent. Naturally one tends to remember one's successes and forget lesser events, but I recount a number of my spectacular failures as clear examples of what to avoid. I have found that the personal story is far, far more effective than the impersonal one; hence there is necessarily an aura of "bragging" in the book that is unavoidable. Let me repeat what I earlier indicated. Apparently an "art" – which almost by definition cannot be put into words – is probably best communicated by approaching it from many sides and doing so repeatedly, hoping thereby students will finally mater enough of the art, or if you wish, style, to significantly increase their future contributions to society. A totally different description of the course is: it covers all kinds of things that could not find their proper place in the standard curriculum.

Key Takeaways

Orientation

1. The purpose of this course is to prepare you for your technical future
2. Vicarious learning from the experiences of others saves making errors yourself, but I regard the study of successes as being basically more important than the study of failure. As I will say several times, there are so many ways of being wrong and so few of being right, studying successes is more efficient, and furthermore when your turn comes you will know how to succeed rather than fail!
3. I am, as it were, only a coach. I cannot run the mile for you; at best I can discuss styles and criticize yours. You know you must run the mile if the athletics course is to be of benefit to you – hence *you* must think carefully about what you hear or read in this book if it is to be effective in changing you – which must obviously be the purpose of ay course. Again, you will get out of this course only as much as you put in, and if you put in little effort beyond sitting in the class or reading the book, then it is simply a waste of your time. *You* must also mull things over, compare what is ay with your own experiences, talk with others, and make some of the points part of your way of doing things.
4. You all recognize there is a significant different between *education* and *training.* Education is what, when, and why to do things, training is how to do it. Either one without the other is not of much use. You need to know both what to do and how to do it. I have already compared mental and physical training and said to a great extent in both you get out of it what you put into it – all the coach can do is suggest styles and criticize a bit now and then…You think education should precede training, but the kind of educating I am trying to do must be based on your past experiences and technical knowledge. Hence this inversion is what might seem to be reasonable. In a real sense I am engaged in "meta-education", the topic of the course is education itself and hence our discussions must rise above it – "meta-education", just as metaphysics was supposed to be above physics in Aristotle's time (actually "follow", "transcend", is the translation of "meta").
5. The reason back of the envelope calculations are widely used by great scientists is clearly revealed – you get a good feeling for the truth or falsity of what was claimed, as well as realize which factors you were inclined not to think about, such as exactly what was meant by the lifetime of a scientist. Having done the calculations, you are much more likely to retain the results in your mind. Furthermore, such calculations keep the ability to model situations fresh and ready for more important applications as they arise. Thus, I

recommend when you hear quantitative remarks such as the above you turn to a quick modeling to see if you believe what is being said, especially when given in the public media like the press and TV. Very often you find what is being said is nonsense, either no definite statement is made which you can model, or if you can set up the model then the results of the model do not agree with what was said. I found it very valuable at the physics table I used to eat with; I sometimes cleared up misconceptions at the time they were being formed, thus advancing matters significantly.

6. How to deal with constant change? One answer is you must concentrate on the fundamentals, at least what *you think* at the time are fundamentals, and also develop the ability to learn new fields of knowledge when they arise so you will not be left behind, as so many good engineers are in the long run…How are you to recognize "fundamentals"? One test is they have lasted a long time. Another test is from the fundamentals all the rest of the field can be derived by using the standard methods in the field…But you will simply have to actively master *on your own* the many new emerging fields as they arise, without having the luxury of being passively taught.
7. I need to discuss science vs. engineering. Put glibly: in science if you know what you are doing you should not be doing it. In engineering if you do not know what you are doing you should not be doing it.
8. In any case I will often use history as a background for the extrapolations I make. I believe the best predictions are based on understanding the fundamental forces involved, and this is what I depend on mainly. Often it is not physical limitations which control but rather it is human made laws, habits, and organizational rules, regulations, personal egos, and inertia, which dominate the evolution to the future. You have not been trained along these lines as much as I believe you should have been, and hence I must be careful to include them whenever the topics arise.
9. There is a saying, "Short term predictions are always optimistic and long-term predictions are always pessimistic." The reason, so it is claimed, the second part is true is for most people the geometric growth due to the compounding of knowledge is hard to grasp.
10. I shall use history as a guide many times in spite of Henry Ford, Sr. saying, "History is Bunk". Probably Ford's points were: a) History is seldom reported at all accurately, and I have found no two reports of what happened at Los Alamos during WW-II seems to agree and b) Due to the pace of progress the future is rather disconnected from the past; the presence of the modern computer is an example of the great differences which have arisen. Reading some historians, you get the impression the past was determined by big trends, but you also have the feeling the future has great possibilities. You can handle

this apparent contradiction in at least four ways: 1) You can simply ignore it. 2) You can admit it. 3) You can decide the past was a lot less determined than historians usually indicate and individual choices can make large differences at times. Alexander the Great, Napoleon, and Hitler had great effects on the physical side of life, while Pythagoras, Plato, Aristotle, Newton, Maxwell, and Einstein are examples on the mental side. 4) You can decide the future is less open ended than you would like to believe, and there is really less choice than there appears to be. It is probable the future will be more limited by the slow evolution of the human animal and the corresponding human laws, social institution, and organizations than it will be by the rapid evolution of technology. In spite of the difficulty of predicting the future and that: Unforeseen technological inventions can completely upset the most careful predictions, you must try to foresee the future you will face. To illustrate the importance of this point of trying to foresee the future I often use a standard story. It is well known the drunken sailor who staggers to the left or right with n independent random steps will, on the average, end up about the square root of n steps from the origin. But if there is a pretty girl in one direction, then his steps will tend to go in that direction, and he will go a distance proportional to n. In a lifetime of many, many independent choices, small and large, a career with a vision will get you a distance proportional to n, while no vision will get you only the distance square root n. In a sense, the main difference between those who go far and those who do not is some people have a vision and the others do not and therefore can only react to the current events as they happen. One of the main tasks of this course is to start you on the path of creating in some detail *your* vision of *your* future…No vision, not much of a future. To what extent history does or does not repeat itself is a moot question. But it is one of the few guides you have; hence history will often play a large role in my discussions – I am trying to provide you with some perspective as a possible guide to create your vision of your future. The other main tool I have used is an active imagination in trying to see what will happen. For many years I devoted about 10% of my time (Friday afternoons) to trying to understand what would happen in the future of computing, both as a scientific tool and as a shaper of the social world of work and play. In forming your plan for your future, you need to distinguish three different questions: what is possible? What is likely to happen? What is desirable to happen. In a sense the first is Science—what is possible. The second in Engineering—what are the human factors which chose the one future that does happen from the ensemble of all possible futures. The third, is ethics, morals, or whatever other word you wish to apply to value judgments. It is important to examine all three questions, and in so far as the second differs from the third, you will probably have an idea of how to alter things to make the more desirable future occur, rather than let the inevitable happen and suffer the consequences. Again, you can see why having a vision is what tends to separate the leaders from the followers.

11. The standard process of organizing knowledge by departments, and sub departments, and further breaking it up into separate courses, tends to conceal the homogeneity of knowledge, and at the same time to omit much which falls between the courses. The optimization of the individual courses in turn means a lot of important things in Engineering practice are skipped since they do not appear to be essential to any one course. One of the functions of this book is to mention and illustrate many of these missed topics which are important in the practice of Science and Engineering. Another goal of the course is to show the essential unity of all knowledge rather than the fragments which appear as the individual topics are taught. In your future anything and everything you know might be useful, but if you believe the problem is in one area you are not apt to use information that is relevant, but which occurred in another course.
12. Lastly, in a sense, this is a religious course—I am preaching the message that, with apparently only one life to live on this earth, you ought to try to make significant contributions to humanity rather than just get along through life comfortably—that the life of trying to achieve excellence in some area is in itself a worthy goal for your life. It has often been observed the true gain is in the struggle and not in the achievement—a life without a struggle on your part to make yourself excellent is hardly a life worth living. This, it must be observed, is an opinion and not a fact, but it is based on observing many people's lives and speculating on their total happiness rather than the moment to moment pleasures they enjoyed. Again, this opinion of their happiness must be my own interpretation as no one can know another's life. Many reports by people who have written about the "good life" agree with the above opinion. Notice I leave it to you to pick your goals of excellence but claim only a life without such a goal is not really living but it is merely existing—in my opinion. In ancient Greece Socrates (469–399) said: The unexamined life is not worth living.

Foundations of Digital (Discrete)

1. Indeed, one of the major items in the conversion from hand to machine production is the imaginative redesign of an equivalent product. Thus, in thinking of mechanizing a large organization, it won't work if you try to keep things in detail exactly the same, rather there must be a larger give-and-take if there is to be a significant success. You must get the essentials of the job in mind and then design the mechanization to do that job rather than trying to mechanize the current version—if you want a significant success in the

long run. I need to stress this point; mechanization requires you produce an equivalent product, not identically the same one. Furthermore, in any design it is now essential to consider field maintenance since in the long run it often dominates all other costs. The more complex the designed system the more field maintenance must be central to the final design. Only when field maintenance is part of the original design can it be safely controlled; it is not wise to try to graft it on later. This applies to both mechanical things and to human organizations.

2. But you were all taught about the evils of the Middle Age scholasticism—people deciding what would happen by reading in the books of Aristotle (384–322) rather than looking at Nature. This was Galileo's (1564–1642) great point which started the modern scientific revolution—look at Nature not in books! But what was I saying above? We are now looking more and more in books and less and less at Nature! There is clearly a risk we will go too far occasionally—and I expect this will happen frequently in the future. We must not forget, in all the enthusiasm for computer simulations, occasionally we must look at Nature as She is.
3. Computers have also greatly affected Engineering. Not only can we design and build far more complex things than we could by hand, we can explore many more alternate designs. We also now use computers to control situations such as on the modern high-speed airplane where we build unstable designs and then use high speed detection and computers to stabilize them since the unaided pilot simply cannot fly them directly. Similarly, we can now do unstable experiments in the laboratories using a fast computer to control the instability. The result will be that the experiment will measure something very accurately right on the edge of stability.
4. Among other evils of micromanagement is lower management does not get the chance to make responsible decisions and learn from their mistakes, but rather because the older people finally retire then lower management finds itself as top management —without having had many real experiences in management! Furthermore, central planning has been repeatedly shown to give poor results (consider the Russian experiment for example or our own bureaucracy). The persons on the spot usually have better knowledge than can those at the top and hence can often (not always) make better decisions if things are not micromanaged. The people at the bottom do not have the larger, global view, but at the top they do not have the local view of all the details, many of which can often be very important, so either extreme gets poor results. Next, an idea which arises in the field, based on the direct experience of the people doing the job, cannot get going in a centrally controlled system since the managers did not think of it themselves. The not invented here (NIH) syndrome is one of the major curses of our society, and computers with their

ability to encourage micromanagement are a significant factor. There is slowly coming, but apparently definitely, a counter trend to micromanagement. Loose connections between small, somewhat independent organizations, are gradually arising. Thus, in the brokerage business one company has set itself up to sell its services to other small subscribers, for example, computer and legal services. This leaves the brokerage decisions of their customers to the local management people who are close to the front line of activity. Similarly, in the pharmaceutical area some loosely related companies carry out their work and intertrade among themselves as they see fit. I believe you can expect to see much more of this loose association between small organizations as a defense against micromanagement from the top which occurs so often in big organizations. There has always been some independence of subdivisions in organizations, but the power to micromanage from the top has apparently destroyed the conventional lines and autonomy of decision making—and I doubt the ability of most top managements to resist for long the power to micromanage.

5. Since, as I have been repeatedly said, technical progress is going on at an increasing rate, it follows technological obsolescence will be much more rapid in the future than it is now. You will hardly get a system installed and working before there are significant improvements which you can adapt by mere program changes If you have used general purpose chips and good programming methods rather than your special purpose chip which will almost certainly tie you down to your first design. Hence beware of special purpose chips! Though many times they are essential.

History of Computers (Hardware)

1. Again, to reduce things to human size. When I first got digital computing really going inside Bell Telephone Laboratories I began by renting computers outside for so many hours the head of the Mathematics department figured out for himself it would be cheaper to get me one inside—a deliberate plot on my part to avoid arguing with him as I thought it useless and would only produce more resistance on his part to digital computers. Once a boss says "no!" it is very hard to get a different decision, so don't let them say "No!" to a proposal. I found in my early years I was doubling the number of computations per year about every 15 months. Some years later I was reduced to doubling the amount about every 18 months. The department head kept telling me I could not go on at that rate forever, and my polite reply was always, "You are right, of course, but you just watch me double the amount of computing every 18–20 months!" Because the machines available kept up the corresponding rate enabled me, and my

successors, for many years to double the amount of computing done. We lived on the almost straight-line part of the "S" curve all those years

2. The purpose of computing is insight, not numbers

History of Computes (Software)

1. To see the obvious, it often takes an outsider, or else someone like me who is thoughtful and wonders what he is doing and why it is all necessary. Even when told, the old timers will persist in the ways they learned, probably out of pride for their past and an unwillingness to admit there are better ways than those they were using for so long
2. History tends to be charitable in this matter. It gives credit for understanding what something means when we first to do it. But there is a wise saying, "Almost everyone who opens up a new field does not really understand it the way the followers do". The evidence for this is, unfortunately, all too good. It has been said in physics no creator of any significant thing ever understood what he had done. I never found Einstein on the special relativity theory as clear as some later commentators. And at least one friend of mine has said, behind my back, "Hamming doesn't seem to understand error correcting codes!" He is probably right; I do not understand what I invented as clearly as he does. The reason this happens so often is the creators have to fight through so many dark difficulties, and wade through so much misunderstanding and confusion, they cannot see the light as others can, now the door is open, and the path made easy.
3. 4 rules for designing a language: easy to learn, easy to use, easy to debug (find and correct errors), easy to use subroutines
4. While each has some merit, I have faith in only one which is almost never mentioned—think before you write the program, it might be called. Before you start, think carefully about the whole thing including what will be your acceptance test it is right, as well as how later field maintenance will be done. Getting it right the first time is much better than fixing it up later!
5. What other very general pieces of programming can be similarly done is not now known—you can think about it as one possible solution to the "programming problem". In the Chapter on hardware I carefully discussed some of the limits—the size of molecules, the velocity of light, and the removal of heat. I should summarize correspondingly the less firm limits of software. I made the comparison of writing software with the act of literary writing; both seem to depend fundamentally on clear thinking. Can good programming be taught? If we look at the corresponding teaching of "creative writing" courses we find most students of such courses do not become great

writers, and most great writers in the past did not take creative writing courses! Hence it is dubious that great programmers can be trained easily. Does experience help? Do bureaucrats after years of writing reports and instructions get better? I have no real data, but I suspect with time they get worse! The habitual use of "governmentese" over the years probably seeps into their writing style and makes them worse. I suspect the same for programmers! Neither years of experience nor the number of languages used is any reason for thinking the programmer is getting better from these experiences. An examination of books on programming suggests most of the authors are not good programmers! The results I picture are not nice, but all you have to oppose it is wishful thinking—I have evidence of years and years of programming on my side!

History of Computer Application

1. You should always feel some excitement when you give a talk since even the best actors and actresses usually have some stage fright. Your excitement tends to be communicated to the audience, and if you seem to be perfectly relaxed then the audience also relaxes and may fall asleep! The talk also kept me up to date, made me keep an eye out for trends in computing, and generally paid off to me in intellectual ways as well as getting me to be a more polished speaker. It was not all just luck—I made a lot of it by trying to understand, below the surface level, what was going on. I began, at any lecture I attended anywhere, to pay attention not only to what was said, but to the style in which it was said, and whether it was an effective or a noneffective talk. Those talks which were merely funny I tended to ignore, though I studied the style of joke telling closely. An after-dinner speech requires, generally, three good jokes; one at the beginning, one in the middle, and a closing one so that they will at least remember one joke; all jokes of course told well. I had to find my own style of joke telling, and I practiced it by telling jokes to secretaries
2. This is typical of many situations. It is first necessary to prove beyond any doubt the new thing, device, method, or whatever it is, can cope with heroic tasks before it can get into the system to do the more routine, and in the long run, more useful tasks. Any innovation is always against such a barrier, so do not get discouraged when you find your new idea is stoutly, and perhaps foolishly, resisted. By realizing the magnitude of the actual task, you can then decide if it is worth your efforts to continue, or if you should go do something else you can accomplish and not fritter away your efforts needlessly against the forces of inertia and stupidity.

3. When you successfully use a computer you usually do an equivalent job, not the same old one. Again, you see the presence of the computer, in the long run, changed the nature of many of the experiments we did.

Artificial Intelligence – I, II, III

1. You must struggle with your own beliefs if you are to make any progress in understanding the possibilities and limitations of computers in the intellectual area. To do this adequately you must formalize your beliefs and then criticize them severely, arguing one side against the other, until you have a fair idea of the strengths and weakness of both sides
2. One can claim the checker playing program "learned" and the geometry theorem proving program showed "creativity", "originality", or whatever you care to call it. They are but a pair of examples of many similar programs which have been written. The difficulty in convincing you the programs have the claimed properties is simply once a program exists to do something you immediately regard what is done as involving nothing other than a rote routine, even when random numbers obtained from the real world are included in the program. Thus, we have the paradox; the existence of the program automatically turns you against believing it is other than a rote process. With this attitude, of course, the machine can never demonstrate it is more than a "machine" in the classical sense, there is no way it can demonstrate, for example, it can "think".
3. Perhaps thinking should be measured not by what you do but how you do it.
4. All too often people report on past and present applications, which is good, but not on the topic whose purpose is to sensitize you to future possibilities you might exploit. It is hard to get people to aggressively think about how things in their own area might be done differently. I have sometimes wondered whether it might be better if I asked people to apply computers to other areas of application than their own narrow speciality; perhaps they would be less inhibited there!

Coding Theory

1. I have repeatedly indicated I believe the future will be increasingly concerned with information in the form of symbols, and less concerned with material things, hence the theory of encoding (representing) information in convenient codes is a non-trivial topic. The above material gave a simple error detecting code for machine-like situations, as well as a weighted code for human use. They are but two examples of what coding

theory can contribute to an organization in places where machine and human errors can occur.

Error Correcting Codes

1. Notice first this essential step happened only because there was a great deal of emotional stress on me at the moment, and this is characteristic of most great discoveries. Working calmly will let you elaborate and extend things, but the break throughs generally come only after great frustration and emotional involvement. The calm, cool, uninvolved researcher seldom makes really great, new steps.
2. Of course, as you go through life you do not know what you are preparing yourself for—only you want to do significant things and not spend the whole of your life being a "janitor of science" or whatever your profession is. Of course, luck plays a prominent role. But so far as I can see, life presents you with many, many opportunities for doing great things (define them as you will) and the prepared person usually hits one or more successes, and the unprepared person will miss almost every time. The above opinion is not based on this one experience, or merely on my own experiences, it is the result of studying the lives of many great scientists. I wanted to be a scientist hence I studied them, and I looked into discoveries which happened where I was and asked questions of those who did them. This opinion is also based on common sense. You establish in yourself the style of doing great things, and then when opportunity comes you almost automatically respond with greatness in your actions. You have trained yourself to think and act in the proper ways. There is one nasty thing to be mentioned, however, what it takes to be great in one age is not what is required in the next one. Thus you, in preparing yourself for future greatness (and the possibility of greatness is more common and easy to achieve than you think, since it is not common to recognize greatness when it happens under one's nose) you have to think of the nature of the future you will live in. The past is a partial guide, and about the only one you have besides history is the constant use of your own imagination. Again, a random walk of random decisions will not get you anywhere near as far as those taken with your own vision of what your future should be. I have both told and shown you how to be great; now you have no excuse for not doing so!

Information Theory

1. Shannon identified information with *surprise.* He chose the negative of the log of the probability of an event as the amount of information you get when the event of probability p happens. For example, if I tell you it is smoggy in Los Angles then p is near 1 and that is not much information, but if I tell you it is raining in Monterey in June then that is surprising and represents more information. Because log 1=0 the certain event contains no information…Let us pause and examine what has happened so far. First, we have not defined "information", we merely gave a formula for measuring the amount. Second, the measure depends on surprise, and while it does match, to a reasonable degree, the situation with machines, say the telephone system, radio, television, computers, and such, it simply does not represent the normal human attitude towards information. Third, it is a relative measure, it depends on the state of your knowledge. If you are looking at a stream of "random numbers" from a random source then you think each number comes as a surprise, but if you know the formula for computing the "random numbers" then the next number contains no surprise at all, hence contains no information! Thus, while the definition Shannon made for information is appropriate in many respects for machines, it does not seem to fit the human use of the word. This is the reason it should have been called "Communication Theory", and not "Information Theory". It is too late to undo the definition (which produced so much of its initial popularity, and still makes people think it handles "information") so we have to live with it, but you should clearly realize how much it distorts the common view of information and deals with something else, which Shannon took to be surprise.
2. We will now take up an example where a definition still bothers us, namely IQ. It is as circular as you could wish. A test is made up which is supposed to measure "intelligence", it is revised to make it as consistent internally as we can, and then it is declared, when calibrated by a simple method, to measure "intelligence" which is now normally distributed (via the calibration curve). All definitions should be inspected, not only when first proposed, but much later when you see how they are going to enter into the conclusions drawn. To what extent were the definitions framed as they were to get the desired result? How often were the definitions framed under one condition and are now being applied under quite different conditions? All too often these are true! And it will probably be more and more true as we go farther and farther into the softer sciences, which is inevitable during your life time.
3. There is the famous story by Eddington about some people who went fishing in the sea with a net. Upon examining the size of the fish, they had caught they decided there was a

minimum size to the fish in the sea! Their conclusion arose from the tool used and not from reality.

Digital Filters – I, II, III, IV

1. Those who claimed there was no essential difference never made any significant contributions to the development of computers. Those who did make significant contributions viewed computers as something new to be studied on their own merits and not as merely more of the same old desk calculators, perhaps souped up a bit. This is a common, endlessly made, mistake; people always want to think that something new is just like the past—they like to be comfortable in their minds as well as their bodies—and hence they prevent themselves from making any significant contribution to the new field being created under their noses. Not everything which is said to be new really is new, and it is hard to decide in some cases when something is new, yet the all too common reaction of, "It's nothing new." is stupid. When something is claimed to be new, do not be too hasty to think it is just the past slightly improved—it may be a great opportunity for you to do significant things. But again, it may be nothing new.
2. It must be your friends, in some sense, who make you famous by quoting and citing you, and it pays, so I claim, to be helpful to others as they try to do their work. They may in time give you credit for the work, which is better than trying to claim it yourself. Cooperation is essential in these days of complex projects; the day of the individual worker is dying fast. Team work is more and more essential, and hence learning to work in a team, indeed possibly seeking out places where you can help others, is a good idea. In any case the fun of working with good people on important problems is more pleasure than the resulting fame. And the choice of important problems means generally management will be willing to supply all the assistance you need. In my many years of doing computing at Bell Telephone Laboratories I was very careful never to write up a result which involved any of the physics of the situation lest I get a reputation for "stealing other's ideas". Instead I let them write up the results, and if they wanted me to be a co-author, fine! Teamwork implies a very careful consideration for others and their contributions, and they may see their contributions in a different light than you do!
3. Moral: when you know something cannot be done, also remember the essential reason why, so later, when the circumstances have changed, you will not say, "It can't be done". Think of my error! How much more stupid can anyone be? Fortunately for my ego, it is a common mistake (and I have done it more than once) but due to my goof on the FFT I am very sensitive to it now. I also note when others do it—which is all too often! Please

remember the story of how stupid I was and what I missed, and not make that mistake yourself. When you decide something is not possible, don't say at a later date it is still impossible without first reviewing all the details of why you originally were right in saying it couldn't be done.

4. Let us analyze carefully what we do and its implications, because what we do to a great extent controls what we can see. There is, usually, in our imaginations at least, a continuous signal
5. Once again, a wide spread misinterpretation of a result because of a lack of understanding of the basics behind the mathematical tool, and only knowing the tool itself. A little knowledge is a dangerous thing—especially if you lack the fundamentals!
6. Well, the plumber had put nice, large diameter pipes in the shower, Figure 17.I. As a result, in the morning when I started my shower it was too cold, so I turned up the hot water knob, still too cool, so more, still too cool, and more, and then when it was the right temperature, I got in. But of course, it got hotter and hotter as the water which was admitted earlier finally got up the pipe and I had to get out and try again to find a suitable adjustment of the knob. The delay in the hot water getting to me was the trouble. I found myself, in spite of many experiences, in the same classic hunting situation of instability. You can either view my response as being too strong (I was too violent in my actions), or else the detection of the signal was too much delayed, (I was too hasty in getting into the tub). Same effect in the long run! Instability! I never really got to accept the large delay I had to cope with, hence I daily had a minor trouble first thing in the morning! In this graphic example you see the essence of instability.
7. If you will only ask yourself, "Is what I am being told really true?" it is amazing how much you can find is, or borders on, being false, even in a well-developed field! In Chapter 26 I will take up the problem of dealing with the expert. Here you see a simple example of what happens all too often. The experts were told something in class when they were students first learning things, and at the time they did not question it. It becomes an accepted fact, which they repeat and never really examine to see if what they are saying is true or not, especially in their current situation
8. My contribution? Mainly, first identifying the problem, next getting the right people together, then monitoring Kaiser to keep him straight on the fact filtering need not have exclusively to do with time signals, and finally, reminding them of what they knew from statistics (or should have known and probably did not). It seems to me from my experience this role is increasingly needed as people get to be more highly specialized and narrower and narrower in their knowledge. Someone has to keep the larger view and see to it things are done honestly. I think I came by this role from long a long education

in the hands of John Tukey, plus a good basic grounding in the form of the universal tool of Science, namely Mathematics. I will talk in Chapter 23 about the nature of Mathematics.

9. In closing, if you do not, now and then, doubt accepted rules it is unlikely you will be a leader into new areas; if you doubt too much you will be paralyzed and will do nothing. When to doubt, when to examine the basics, when to think for yourself, and when to go on and accept things as they are, is a matter of style, and I can give no simple formula on how to decide. You must learn from your own study of life. Big advances usually come from significant changes in the underlying beliefs of a field. As our state of knowledge advances the balances between aspects of doing research change. Similarly, when you are young then serendipity has probably a long time to pay off, but when you are old it has little time and you should concentrate more on what is at hand.

Simulation – I, II, III

1. A major use of computers these days, after writing and text editing, graphics, program compilation, etc. is simulation. A simulation is the answer to the question: "What if…?" What if we do this? What if this is what happened?
2. This already illustrates a main point I want to make. It is necessary to have a great deal of special knowledge in the field of application. Indeed, I tend to regard many of the courses you have taken, and will take, as merely supplying the corresponding expert knowledge. I want to emphasize this obvious necessity for expert knowledge—all too often I have seen experts in simulation ignore this elementary fact and think they could safely do simulations on their own. Only an expert in the field of application can know if what you have failed to include is vital to the accuracy of the simulation, or if it can safely be ignored.
3. This is fundamental theme I must dwell on. When the simulation has a great deal of stability, meaning resistance to small changes in its overall behavior, then a simulation is quite feasible; but when small changes in some details can produce greatly different outcomes then a simulation is a difficult thing to carry out accurately. Of course, there is long term stability in the weather; the seasons follow their appointed rounds regardless of small details. Thus, there is both short term (day to day) instabilities in the weather, and longer term (year to year) stabilities as well. But the ice ages show there are also very long-term instabilities in the weather, with apparently even longer stabilities!
4. With some delay due to other users wanting their time on the RDA #2, I was soon back and running again, but with a lot more wisdom and experience. Again, I developed a

feeling for the behavior of the missile—I got to "feel" the forces on it as various programs of trajectory shaping were tried. Hanging over the output plotters as the solution slowly appeared gave me the time to absorb what was happening. I have often wondered what would have happened if I had had a modern, high speed computer. Would I ever have acquired the feeling for the missile, upon which so much depended in the final design? I often doubt hundreds more trajectories would have taught me as much—I simply do not know. But that is why I am suspicious, to this day, of getting too many solutions and not doing enough very careful thinking about what you have seen. Volume output seems to me to be a poor substitute for acquiring an intimate feeling for the situation being simulated.

5. Of course, these early simulations used a simple atmosphere of exponential decrease in density as you go up, and other simplifications, which in simulations done years later were all modified. This brings up another belief of mine—doing simple simulations at the early stages lets you get insights into the whole system which would be disguised in any full-scale simulation. I strongly advise, when possible, to start with the simple simulation and evolve it to a more complete, more accurate, simulation later so the insights can arise early. Of course, at the end, as you freeze the final design, you must put in all the small effects which could matter in the final performance. But (1) start as simply as you can provided you include all the main effects, (2) get the insights, and then (3) evolve the simulation to the fully detailed one.
6. Why tell the story? Because it illustrates another point I want to make—an active mind can contribute to a simulation even when you are dealing with experts in a field where you are a strict amateur. You, with your hands on all the small details, have a chance to see what they have not seen, and to make significant contributions, as well as save machine time! Again, all too often I have seen things missed during the simulation by those running it, and hence were not likely to get to the users of the results. One major step you must do, and I want to emphasize this, is to make the effort to master their jargon. Every field seems to have its special jargon, one which tends to obscure what is going on from the outsider-and also, at times, from the insiders! Beware of jargon—learn to recognize it for what it is, a special language to facilitate communication over a restricted area of things or events. But it also blocks thinking outside the original area for which is was designed to cover. Jargon is both a necessity and a curse. You should realize you need to be active intellectually to gain the advantages of the jargon and to avoid the pitfalls, even in your own area of expertise!...Hence this instinctive use of jargon when an outsider comes around should be consciously resisted at all times—we

now work in much larger units than those of cave man and we must try continually to overwrite this earlier design feature in us.

7. That is what you can expect from simulation experts— they are concerned with the simulation and have little or no regard for reality, or even "observed reality".
8. Remember this fact, older minds have more trouble adjusting to new ideas than do younger minds since you will be showing new ideas, and even making formal presentations to, older people throughout much of your career. That your children could understand what you are showing is of little relevance to whether or not the audience to whom you are running the exhibition can. It was a terrible lesson I had to learn, and I have tried not to make that mistake again. Old people are not very quick to grasp new ideas—it is not they are dumb, stupid, or anything else like that, it is simply older minds are usually slow to adjust to radically new ideas
9. Thus, beware of any simulation of a situation which allows the human to use the output to alter their behavior patterns for their own benefit, since they will do so whenever they can.
10. In summary, the reliability of a simulation, of which you will see many in your career since it is becoming increasingly common, is of vital importance. It is not something you can take for granted just because a big machine gives out nicely printed sheets, or displays nice, colorful pictures. You are responsible for your decisions and cannot blame them on those who do the simulations, much as you wish you could. Reliability is a central question with no easy answers.
11. I will continue the general trend of the last chapter, but center on the old expression "garbage in, garbage out", often abbreviated GIGO. The idea is if you put ill-determined numbers and equations (garbage) in then you can only get ill-determined results (garbage) out. By implication the converse is tacitly assumed, if what goes in is accurate then what comes out must be accurate. I shall show both of these assumptions can be false.
12. But my friend, being the kind of person, he was, had connected the lights to a random source! One day he observed to me that no person in all the tests (and they were all high-class Bell Telephone Laboratories scientists) ever said there was no message. I promptly observed to him not one of them was either a statistician or an information theorist, the two classes of people who are intimately familiar with randomness. A check revealed I was right! This is a sad commentary on your education. You are lovingly taught how one theory was displaced by another, but you are seldom taught to replace a nice theory with nothing but randomness! And this is what was needed; the ability to say the theory you just read is no good and there was no definite pattern in the data, only randomness. I

must dwell on this point. Statisticians regularly ask themselves, "Is what I am seeing really there, or is it merely random noise?"

13. From the process of working back and forth between assumptions about the parts and the observed behavior of the whole, we improve our understanding of the structure and dynamics of the system. This book is the result of several cycles of reexamination and revision by the author".
14. The "What if…?" will arise often in your futures, hence the need for you to master the concepts and possibilities of simulations and be ready to question the results and to dig into the details when necessary.

Fiber Optics

1. If a major drop in switching costs came about, how would you design a computer? Would the von Neumann basic design survive at all? What would be the appropriate computer designs with this new cost structure? You can try, as I indicated above, to keep reasonably abreast by actively anticipating the way things and ideas might go, and then seeing what actually happens. Your anticipation means you are far, far better prepared to absorb the new things when they arise than if you sit passively by and merely follow progress. "Luck favors the prepared mind."
2. I have said again and again in this book, my duty as a professor is to increase the probability you will be a significant contributor to our society, and I can think of no better way than establishing in you the habit of anticipating things and leading rather than passively following. It seems to me I must, to accomplish my duty to you and to the institution, move as many of you as I can from a passive to a more active, anticipating role.

Computer Aided Instruction

1. There is a story from ancient Greek times of a Mathematician telling a ruler there were royal roads for him to walk on, and royal messengers to carry his mail, but there was no royal road to geometry. Similarly, you will recognize money and coaching will do only a little for you if you want to run a four-minute mile. There is no easy way for you to do it. The four-minute mile is much the same for everyone. There is a long history of people wanting an easy path to learning. Aldous Huxley, in his book Brave New World discusses the idea of learning while sleeping via a microphone under your pillow telling you things while you sleep, and he exposes the severe limitations of it. During my years

at the Bell Telephone Laboratories the Dianetic movement arose and promised it could "clear" your brain of all its errors and then you would be able to reason perfectly. There are still Dianetic Institutes, but the consensus is against them— particularly as the people produced by them seem not to have dominated any sector of human activities, let alone all sectors. Another organization promises to reveal the secrets of the ancients (who were, somehow, so much smarter than we are now). We have endless ads for speed reading, speed learning, etc., all of which promise, in one way or another, to greatly improve your mind without the hard labor most of us have to put in if we want to succeed. The test of all the previous proposals is not one of them has, as yet, produced a significant number of exceptional people (that we know of at present). As Fermi said about the Extra-Terrestrial Intelligence and UFO people, "Where are they, and why have we not met them?"

2. Beware of the power of wishful thinking on your part—you would like it to be true, so you assume it is true! There is another important factor, known as the Hawthorne effect, it is necessary to explain. At the Hawthorne plant of Western Electric, long, long ago, some psychologists were trying to improve productivity by various changes in the environment. They painted the walls an attractive color, and productivity rose. They made the lighting softer and productivity rose. Each change caused productivity to rise. One of the men got a bit suspicious and sneaked a change back to the original state and productivity rose! Why? It appears when you show you care then the person on the other end responds more favorably than if you appear not to care. The workers all thought the changes were being made for their benefit and they responded accordingly.
3. We now turn to airplane pilot training in the current trainers. They again do a better job, by far, than can any real-life experience, and generally the pilots have fairly little other human interactive training during the course. Flying, to a fair extent, I point out, is a conditioned response is being trained into the human. It is not much thinking, though at times thinking is necessary, it is more training to react rapidly and correctly, both mentally and physically, to unforeseen emergencies
4. What you learn from others you can use to follow; What you learn for yourself you can use to lead.
5. I argued the speed in learning was a significant matter to organizations—rapid learners were much more valuable than were slow learners (other things being the same); it was part of our job to increase the speed of learning and mark for society those who were the better ones. Again, this is opinion, but surely you do not want very slow learners to be in charge of you. Speed in learning new things is not everything, to be sure, but it seems to me it is an important element.

6. Sounds strange, but that is what is known as the "transfer of training"—the ability to use the same ideas in a new situation. Transfer of training was a large part of my contribution to Bell Telephone Laboratories -I did it quite often, though of course I do not know how many chances I missed!
7. Thus, I am wary of proposed changes until the consequences have been followed out carefully through long term predictions of all necessary needs for the material they are now going to omit.

Mathematics

1. As you live your life your attention is generally on the foreground things, and the background is usually taken for granted. We take for granted, most of the time, air, water, and many other things such as language and Mathematics. When you have worked in an organization for a long time its structure, its methods, its "ethos" if you wish, are usually taken for granted. It is worthwhile, now and then, to examine these background things which have never held your close attention before, since great steps forward often arise from such actions, and seldom otherwise. It is for this reason we will examine Mathematics, though a similar examination of language would also prove fruitful. We have been using Mathematics without ever discussing what it is—most of you have never really thought about it, you just did the Mathematics—but Mathematics plays a central role in science and engineering. Perhaps the favorite definition of Mathematics given by Mathematicians is: "Mathematics is what is done by Mathematicians, and Mathematicians are those who do Mathematics". Coming from a Mathematician its circularity is a source of humor, but it is also a clear admission they do not think Mathematics can be defined adequately. There is a famous book, What is Mathematics, and in it the authors exhibit Mathematics but do not attempt to define it. Once at a cocktail party a Bell Telephone Laboratories Mathematics department head said three times to a young lady, Mathematics is nothing but clear thinking. I doubt she agreed, but she finally changed the subject; it made an impression on me. You might also say Mathematics is the language of clear thinking.
2. Apparently, as I said above, meaning arises from the use made of the word, and is not otherwise defined. Some years back a famous dictionary came out and admitted they could not prescribe usage, they could only say how words were used; they had to be "descriptive" and not "prescriptive". That there is apparently no absolute, proper meaning for every word made many people quite angry. For example, both the New Yorker book reviewer and the fictional detective Nero Wolfe were very irate over the

dictionary. We now see all this "truth" which is supposed to reside in Mathematics is a mirage. It is all arbitrary, human conventions. But we then face the unreasonable effectiveness of Mathematics.

3. Thus, I have gone beyond the limitations of Gödel's theorem, which loosely states if you have a reasonably rich system of discrete symbols (the theorem does not refer to Mathematics in spite of the way it is usually presented) then there will be statements whose truth or falsity cannot be proved within the system. It follows if you add new assumptions to settle these theorems, there will be new theorems which you cannot settle within the new enlarged system. This indicates a clear limitation on what discrete symbol systems can do.

Quantum Mechanics

1. Most physicists currently believe they have the basic description of the universe [though they currently admit 90% to 99% of the universe is in the form of "dark matter" of which they know nothing except it has gravitational attraction]. You should realize in all of science there are only descriptions of how things happen and nothing about why they happen. Newton gave us the formula for how gravity worked, and he made no hypotheses as to what gravity really was, nor through what medium it worked, let alone why it worked. Indeed, he did not believe in "action at a distance".
2. Man is not a rational animal, he is a rationalizing animal
3. The Aspect experiments apparently force you to accept non-local effects—what happens at one place is affected by remote things and the effect which is transmitted does not, in any real sense, pass through the local areas in between but gets there immediately. But apparently you cannot use the effect for useful signaling.

Creativity

1. It should be remarked in primitive societies creativity, originality, and novelty are not appreciated, rather doing as one's ancestors did is the proper thing to do. This is also true in many large organizations today; the elders are sure they know how the future should be handled and the younger members of the tribe when they do things differently are not appreciated.

2. Creativity seems, among other things, to be "usefully" putting together things which were not perceived to be related before, and it may be the initial psychological distance between the things which counts most.
3. information and I did not, until he pointed it out to me. Clearly his information retrieval system had many more "hooks" than mine did. At least more useful ones! How could this be? Probably because he was more in the habit than I was of turning over new information again and again so his "hooks" for retrieval were more numerous and significantly better than mine were. Hence wishing I could similarly do what he did, I started to mull over new ideas, trying to make significant "hooks" to relevant information so when later I went fishing for an idea, I had a better chance of finding an analogy. I can only advise you to do what I tried to do —when you learn something new think of other applications of it—ones which have not arisen in your past, but which might in your future. How easy to say, but how hard to do! Yet, what else can I say about how to organize your mind so useful things will be recalled readily at the right time? Many books are written these days on the topic of creativity; we often talk about it, and we even have whole conferences devoted to it, yet we can say so little! There is much talk about having the right surrounding atmosphere—as if that mattered much! I have seen the creative act done under the most trying circumstances. Indeed, I often suspect, as I will later discuss more fully, what the individual regards as ideal conditions for creativity is not what is needed, but rather the constant impinging of reality is often a great help. In the past I have deliberately managed myself in this matter by promising a result by a given date, and then, like a cornered rat, having at the last minute to find something! I have been surprised at how often this simple trick of managing myself has worked for me. Of course, it depends on having a great deal of pride and self-confidence. Without self-confidence you are not likely to create great, new things. There is a thin line between having enough self-confidence and being over-confident. I suppose the difference is whether you succeed or fail; when you win you are strong willed, and when you lose you are stubborn! Back to the topic of whether we can teach creativity or not. From the above you should get the idea I believe it can be taught. It cannot be done with simple tricks and easy methods; what must be done is you must change yourself to be more creative. As I have thought about it in the past, I realize how often I have tried to change myself, so I was more as I wished I were and less as I had been. (Often, I did not succeed!) Changing oneself is not easy, as anyone who has gone on a diet to lose weight can

testify; but that you can indeed change yourself is also evident from the few who do succeed in dieting, quitting smoking, and other changes in habits. We are, in a very real sense, the sum total of our habits, and nothing more; hence by changing our habits, once we understand which ones we should change and in what directions and understand our limitations in changing ourselves, then we are on the path along which we want to go. In planning to change yourself clearly the old Greek saying applies, “Know thyself.” and do not try heroic reformations which are almost certain to fail. Practice on small ones until you gradually build up your ability to change yourself in the larger things. You must learn to walk before you run in this matter of being creative, but I believe it can be done. Furthermore, if you are to succeed (to the extent you secretly wish to) you must become creative in the face of the rapidly changing technology which will dominate your career. Society will not stand still for you, it will evolve more and more rapidly as technology plays an increasing role at all levels of the organization. My job is to make you one of the leaders in this changing world, not a follower, and I am trying my best to alter you, especially in getting you to take charge of yourself and not to depend on others, such as me, to help. The many small stories I have told you about myself are partly to convince you that you can be creative when your turn comes for guiding our society to its possible future. The stories have also been included to show you some possible models of how to do things. I have not yet discussed the delicate topic of dropping a problem. If you cannot drop a wrong problem, then the first time you meet one you will be stuck with it for the rest of your career. Einstein was tremendously creative in his early years, but once he began, in mid-life, the search for a unified theory then he spent the rest of his life on it and had about nothing to show for all the effort. I have seen this many times while watching how Science is done. It is most likely to happen to the very creative people; their previous successes convince them they can solve any problem; but there are other reasons besides over-confidence why, in many fields, sterility sets in with advancing age. Managing a creative career is not an easy task, or else it would often be done. In mathematics, theoretical physics and astrophysics, age seems to be a handicap (all characterized by high, raw creativity) while in music composition, literature, and statesmanship, age and experience seem to be an asset. As valued by Bell Telephone Laboratories in the late 1970s, the first 15 years of my career included all they listed, and for my second 15 years they listed nothing I was very closely associated with! Yes, in my areas the really great things are generally done while the person is young, much as in athletics, and in old age you can turn to coaching (teaching) as I have done. Of course, I do not know your field of expertise to say what effect age will have, but I suspect really great things will be realized fairly young, though it may take years to get them into practice. My advice is if you want to do significant things, now is the time to start thinking (if you have not already done so) and not wait until it is the proper moment—which may never arrive! In closing I want to remind you yet again of Pasteur's remark, "Luck favors the prepared mind". Yes, it is a matter of luck just what you do, it is much less luck you will do something if you prepare yourself to succeed. "Creativity" is just another name for the great successes which make a difference in history.

Experts

1. As remarked in an earlier chapter, as our knowledge grows exponentially, we cope with the growth mainly by specialization. It is increasingly true: An expert is one who knows everything about nothing; A generalist knows nothing about everything. In an argument between a specialist and a generalist the expert usually wins by simply: (1) using unintelligible jargon, and (2) citing their specialist results which are often completely irrelevant to the discussion. The expert is, therefore, a potent factor to be reckoned with in our society. Since experts are both necessary, and also at times do great harm in blocking significant progress, they need to be examined closely. All too often the expert misunderstands the problem at hand, but the generalist cannot carry though their side to completion. The person who thinks they understand the problem and does not is usually more of a curse (blockage) than the person who knows they do not understand the problem.
2. Kuhn, in his book Scientific Revolutions examined the structure of scientific progress and introduced the concept of paradigm (pattern, example) as a description of the normal state of Science. He observed most of the time any particular science has an accepted set of assumptions, often not mentioned or discussed, whose results are taught to the students, and which the students in turn accept without being aware of how extensive these assumptions are. There is also an accepted set of problems and methods of attacking them. The workers in the field proceed in this fashion, extending and elaborating the field endlessly, and simply ignoring any contradictions which may come up. Occasionally, usually because of the contradictions most of the people in the field choose to ignore or simply forget, there will arise a sudden change in the paradigm, and

as a result a new pattern of beliefs comes into dominance, along with the ability to ask new kinds of questions and get new kinds of answers to older problems. These changes in the dominant paradigm of a science usually represent the great steps forward. For example, both special relativity and QM represent such changes in the field of physics. At first the change is resisted by the establishment, which has so much of their past effort invested in the old approach, but usually, so Kuhn and others like to believe, the new triumphs over the old. I suppose if you allow enough time, then that is right, but the number of years may be more than the initiator's lifetime!

3. The record of the experts saying something is impossible just before it is done is amazing.
4. All impossibility proofs must rest on a number of assumptions which may or may not apply in the particular situation. Experts in looking at something new always bring their expertise with them as well as their particular way of looking at things. Whatever does not fit into their frame of reference is dismissed, not seen, or forced to fit into their beliefs. Thus, really new ideas seldom arise from the experts in the field. You cannot blame them too much since it is more economical to try the old, successful ways before trying to find new ways of looking and thinking. All things which are proved to be impossible must obviously rest on some assumptions, and when one or more of these assumptions are not true then the impossibility proof fails—but the expert seldom remembers to carefully inspect the assumptions before making their "impossible" statements. There is an old statement which covers this aspect of the expert. It goes as follows: "If an expert says something can be done, he is probably correct, but if he says it is impossible then consider getting another opinion."
5. In discussing the expert let me introduce another aspect which has barely been mentioned so far. It appears most of the great innovations come from outside the field, and not from the insiders. I cited above continental drift. Consider archaeology. A central problem is the dating of the remains found. In the past this was done by elaborate, unreliable stratigraphy, by estimating the time needed to bury the material where it was found. Now carbon dating is used as the main tool. Where did it come from? Physics! None of the archaeology experts would have ever thought of it. So far as I can make out, the first automatic telephone came from an undertaker who thought he was not getting fair treatment from the telephone company and designed a machine which would be fair. Similar examples occur in most fields of work, but the text books seldom, if ever, discuss this aspect. At the time of Einstein's famous "five papers in one year" he was working in the Swiss patent office! He had not been able to find an official position within the circle of University physics. In fairness to the system, in a few years he was recognized and

offered various prestigious positions, ending up in Berlin. The Nazis later drove him out of Berlin to the Institute of Advanced Study, Princeton. Thus, the expert faces the following dilemma. Outside the field there are a large number of genuine crackpots with their crazy ideas, but among them may also be the crackpot with the new, innovative idea which is going to triumph. What is a rational strategy for the expert to adopt? Most decide they will ignore, as best they can, all crackpots, thus ensuring they will not be part of the new paradigm, if and when it comes. Those experts who do look for the possible innovative crackpot are likely to spend their lives in the futile pursuit of the elusive, rare crackpot with the right idea, the only idea which really matters in the long run. Obviously, the strategy for you to adopt depends on how much you are willing to be merely one of those who served to advance things, vs. the desire to be one of the few who in the long run really matter. I cannot tell you which you should choose that is your choice. But I do say you should be conscious of making the choice as you pursue your career. Do not just drift along; think of what you want to be and how to get there. Do not automatically reject every crazy idea, the moment you hear of it, especially when it comes from outside the official circle of the insiders—it may be the great new approach which will change the paradigm of the field! But also, you cannot afford to pursue every "crackpot" idea you hear about. I have been talking about paradigms of Science, but so far as I know the same applies to most fields of human thought, though I have not investigated them closely. And it probably happens for about the same reasons; the insiders are too sure of themselves, have too much invested in the accepted approaches, and are plain mentally lazy. Think of the history of modern technology you know! With the rapid increase in the use of technology this type of error is going to occur more often, so far as I can see. The experts live in their closed world of theory, certain they are right and are intolerant of other opinions. In some respects, the expert is the curse of our society with their assurance they know everything, and without the decent humility to consider they might be wrong. Where the question looms so important I suggested to you long ago to use in an argument, "What would you accept as evidence you are wrong?" Ask yourself regularly, "Why do I believe whatever I do". Especially in the areas where you are so sure you know; the area of the paradigms of your field.

6. What you did to become successful is likely to be counterproductive when applied at a later date.
7. Civilization is merely a thin veneer we have put on top of our anciently derived instincts, but the veneer is what makes it possible for modern society to operate. Being civilized means, among other things, stopping your immediate response to a situation, and thinking whether it is or is not the appropriate thing to do. I am merely trying to make

you more self-aware so you will be more “civilized” in your responses and hence probably, but not certainly, more successful in attaining the things you want.

Unreliable Data

1. Being me, after a time I asked, “Why do you believe the test equipment is as reliable as what is being tested?” The answer I got convinced me he had not really thought about it, but seeing pursuit of the point was fruitless, I let it drop. But I did not forget the question!
2. If you want to be certain then you are apt to be obsolete.
3. “There is never time to do the job right, but there is always time to fix it later.”
4. From that experience I learned never to process any data until I had first examined it carefully for errors. There have been complaints that I would take too long, but almost always I found errors and when I showed the errors to them, they had to admit I was wise in taking the precautions I did. No matter how sacred the data and urgent the answer, I have learned to pretest it for consistency and outliers at a minimum.
5. Definitions have a habit of changing over time without any formal statement of this fact.
6. Institutions like people, tend to move only when forced to.
7. In my experience most Economists are simply unwilling to discuss the basic inaccuracy in the economic data they use, and hence I have little faith in them as Scientists. But who said Economic Science is a Science? Only the Economists!
8. Second, you cannot gather a really large amount of data accurately. It is a known fact which is constantly ignored. It is always a matter of limited resources and limited time. The management will usually want a 100% survey when a small one, consisting a good deal less, say 1% or even 1/10%, will yield more accurate results! It is known, I say, but ignored. The telephone companies, in order to distribute the income to the various companies involved in a single long-distance phone call, used to take a very small, carefully selected sample, and on the basis of this sample they distributed the money among the partners. The same is now done by the airlines. It took them a long while before they listened, but they finally came to realize the truth of: Small samples carefully taken are better than large samples poorly done. Better, both in lower cost and in greater accuracy.
9. It is much like the famous remark, the average American family has 2 and a fraction children, but of course no family has a fractional child! Averages are meaningful for homogeneous groups (homogeneous with respect to the actions that may later be taken) but for diverse groups averages are often meaningless. As earlier remarked, the average

adult has one breast and one testicle, but that does not represent the average person in our society. If the range of responses is highly skewed, we have recently admitted publicly the median is often preferable to the average (mean) as an indicator. Thus, they often now publish the median income and median price of houses, and not the average amounts.

Systems Engineering

1. Parables are often more effective than is a straight statement
2. To rise to the top, you should have the larger view—at least when you get there.
3. The obligations in each case were of: (1) immediate importance, (2) longer range importance, and (3) very long-term importance. I also realized under (2) and (3) one of my functions in the research department was not so much to solve the existing problems as to develop the methods for solving problems, to expand the range of what could be done, and to educate others in what I had found so they could continue, extend, and improve my earlier efforts. In systems engineering it is easy to say the right words, and many people have learned to say them when asked about systems engineering, but as in many sports such as tennis, golf, and swimming it is hard to do the necessary things as a whole. Hence systems engineers are to be judged not by what they say but by what they produce. There are many people who can talk a good game but are not able to play one. The first rule of systems engineering is: If you optimize the components you will probably ruin the system performance. This is a very difficult point to get across. It seems so reasonable if you make an isolated component better then the whole system will be better—but this is not true, rather the system performance will probably degrade!
4. You probably still do not believe the statement so let me apply this rule to you. Most of you try to pass your individual courses by cramming at the end of the term, which is to a great extent counter-productive, as you well know, to the total education you need. You look at your problem as passing the courses one at a time, or a term at a time, but you know in your hearts what matters is what you emerge with at the end, and what happens at each stage is not as important. During my last two undergraduate college years when I was the University of Chicago, the rule was at the end you had to pass a single exam based on 9 courses in your major field, and another exam based on 6 in your minor field, and these were mainly what mattered, not what grades you got along the way. I, for the first time, came to understand what the system approach to education means. While taking any one course, it was not a matter of passing it, pleasing the professor, or anything like that, it was learning it so at a later date, maybe two years later, I would still

know the things which should be in the course. Cramming is clearly a waste of time. You really know it is, but the behavior of most of you is a flat denial of this truth. So, as I said above, words mean little in judging a systems engineering job, it is what is produced that matters. The professors believe, as do those who are paying the bill for your education, and probably some of you also, what is being taught will probably be very useful in your later careers, but you continue to optimize the components of the system to the detriment of the whole! Systems engineering is a hard trade to follow; it is so easy to get lost in the details! Easy to say; hard to do. This example should show you the reality of my remark many people know the words, but few can actually put them into practice when the time comes for action in the real world. Most of you cannot!

5. The early railroads were surely systems, but it is not clear to me the first builders did not try to get each part optimized and really did not think, until after the whole was going, there was a system to consider— how the parts would intermesh to attain a decent operating system.
6. That brings up another point, which is now well recognized in software for computers, but it applies to hardware too. Things change so fast part of the system design problem is the system will be constantly upgraded in ways you do not now know in any detail! Flexibility must be part of modern design of things and processes. Flexibility built into the design means not only you will be better able to handle the changes which will come after installation, but it also contributes to your own work as the small changes which inevitably arise both in the later stages of design and in the field installation of the system. Part of systems engineering design is to prepare for changes so they can be gracefully made and still not degrade the other parts. Returning to your education, our real problem is not to prepare you for our past, or even the present, but to prepare you for your future. It is for this reason I have stressed the importance of what currently is believed to be the fundamentals of various fields and have deliberately neglected the current details which will probably have a short lifetime. I cited earlier the half-life time of engineering details as being 15 years—half of the details you learn now will probably be useless to you in 15 years.
7. The closer you meet specifications the worse the performance will be when overloaded
8. My solution’s very presence alters the system’s response. The optimal strategy for the individual was clearly opposed to the optimal strategy for the whole of the laboratories, and it is one of the functions of the systems engineer to block most of the local optimization of the individuals of the system and reach for the global optimization for the system.

9. Westerman believes, as I do, while the client has some knowledge of his symptoms, he may not understand the real causes of them, and it is foolish to try to cure the symptoms only. Thus, while the systems engineers must listen to the client, they should also try to extract from the client a deeper understanding of the phenomena. Therefore, part of the job of a systems engineer is to define, in a deeper sense, what the problem is and to pass from the symptoms to the causes. Just as there is no definite system within which the solution is to be found, and the boundaries of the problem are elastic and tend to expand with each round of solution, so too there is often no final solution, yet each cycle of input and solution is worth the effort. A solution which does not prepare for the next round with some increased insight is hardly a solution at all. I suppose the heart of systems engineering is the acceptance here is neither a definite fixed problem nor a final solution, rather evolution is the natural state of affairs. This is, of course, not what you learn in school where you are given definite problems which have definite solutions.
10. Let me close with the observation I have seen many, many solutions offered which solved the wrong problem correctly. In a sense systems engineering is trying to solve the right problem, perhaps a little wrongly, but with the realization the solution is only temporary and later on during the next round of design these accepted faults can be caught provided insight has been obtained. I said it before, but let me say it again, a solution which does not provide greater insight than you had when you began is a poor solution indeed, but it may be all that you can do given the time constraints of the situation. The deeper, long term understanding of the nature of the problem must be the goal of the system engineer, whereas the client always wants prompt relief from the symptoms of his current problem. Again, a conflict leading to a meta systems engineering approach!
11. How different this view is from the one with which we began! It illustrates the point each solution should bring further understanding of the problem; the first symptoms they tell you will not last long once you begin to succeed; the goal will be constantly changing as your and the customer's understanding deepen.

You Get What You Measure

1. You may think the title means if you measure accurately you will get an accurate measurement, and if not then not; but it refers to a much more subtle thing—the way you choose to measure things controls to a large extent what happens. I repeat the story Eddington told about the fishermen who went fishing with a net. They examined the size of the fish they caught and concluded there was a minimum size to the fish in the sea.

The instrument you use clearly affects what you see. The current popular example of this effect is the use of the bottom line of the profit and loss statement every quarter to estimate how well a company is doing, which produces a company interested mainly in short term profits and has little regard to long term profits. If in a rating system everyone starts out at 95% then there is clearly little a person can do to raise their rating but much which will lower the rating; hence the obvious strategy of the personnel is to play things safe, and thus eventually rise to the top. At the higher levels, much as you might want to promote for risk taking, the class of people from whom you may select them is mainly conservative! The rating system in its earlier stages may tend to remove exactly those you want at a later stage. Were you to start with a rating system in which the average person rates around 50% then it would be more balanced; and if you wanted to emphasize risk taking then you might start at the initial rating of 20% or less, thus encouraging people to try to increase their ratings by taking chances since there would be so little to lose if they failed and so much to gain if they succeeded. For risk taking in an organization you must encourage a reasonable degree of risk taking at the early stages, together with promotion, so finally some risk takers can emerge at the top. Of the things you can choose to measure some are hard, firm measurements, such as height and weight, while some are soft such as social attitudes. There is always a tendency to grab the hard, firm measurement, though it may be quite irrelevant as compared to the soft one which in the long run may be much more relevant to your goals. Accuracy of measurement tends to get confused with relevance of measurement, much more than most people believe. That a measurement is accurate, reproducible, and easy to make does not mean it should be done, instead a much poorer one which is more closely related to your goals may be much preferable. For example, in school it is easy to measure training and hard to measure education, and hence you tend to see on final exams an emphasis on the training part and a great neglect of the education part.

2. Again, you get what was measured, and the normal distribution announced is an artifact of the method of measurement and hardly relates to reality.
3. Coding Theory says the entropy (the average surprise) is maximum when the distribution is uniform. You have the most information when all the grades are used equally, as you may recall from Chapter 13 on Information Theory.
4. Thus, people tend to go into the fields which will favor their peculiarities, as they sense them, and then once in the field these features are often further strengthened. Result— poorly balanced, but highly specialized, people— which may often be necessary to succeed in the present situation. In Mathematics, and in Computer Science, a similar effect of initial selection happens. In the earlier stages of Mathematics up through the

Calculus, as well as in Computer Science, grades are closely related to the ability to carry out a lot of details with high reliability. But later, especially in Mathematics, the qualities needed to succeed change and it becomes more proving theorems, patterns of reasoning, and the ability to conjecture new results, new theorems, and new definitions which matter. Still later it is the ability to see the whole of a field as a whole, and not as a lot of fragments. But the grading process has earlier, to a great extent, removed many of those you might want, and indeed are needed at the later stage! It is very similar in Computer Science where the ability to cope with the mass of programming details favors one kind of mind, one which is often negatively correlated with seeing the bigger picture. The personnel employment department also has an effect on who is recruited into the system. If there is recruiting for research, then the typical member of the personnel department in a big organization is not likely to want the right people. Good researchers, because the criterion is, they have originality in Science and Engineering, also means typically they are original in other aspects of their behavior and dress—meaning they do not appeal to the typical recruiter from the personnel department. Hence, as at Bell Telephone Laboratories, usually the research people go out to do the hiring for the research area, and the personnel department shudders! This is not a trivial point, the recruiting of one generation determines the organization's next generation. There is also the vicious feature of promotion in most systems. At the higher levels the current members choose the next generation—and they tend strongly to select people like themselves— people with whom they will feel comfortable. The Board of Directors of a company has a strong control of the officers and next Board members who are put up for election (the results of which is often more or less automatic). You tend to get inbreeding—but also you tend to get an organization personality. Hence the all too common method of promotion by self-selection at the higher levels of an organization has both good and bad features. This is still on the topic you get what you measure as there is a definite matter of evaluation, and the criteria used, though unconscious, are still there… As just mentioned, a rating system which allows those who are in to select the next generation has both good and bad features and needs to be watched closely for too much inbreeding. Some inbreeding means a common point of view and more harmonious operation from day to day, but also it will probably not have great innovations in the future. I suspect in the future, where I believe change will be the normal state of things, this will become a more serious matter than it has been in the past—and it has definitely been a problem in the past!

5. Although measuring is clearly bad when done poorly, there is no escape from making measurements, rating things, people, etc. Only one person can be the head of an organization at one time, and in the selection, there has to be a reduction to a simple

scale of rating so a comparison can be made. Never mind humans are at least as complex as vectors, and probably even more complex than matrices or tensors of numbers; the complex human, plus the effect of the environment they operate in, must somehow be reduced to a simple measure which makes an ordered array of choices. This may be done internally in the mind, without benefit of conscious thinking, but it must be done whether you believe in rating people or not-there is no escape in any society in which there are differences in rank, power to manage, or whatever other feature you wish. Even on a program of entertainment, there has to be a first and a last performer—all cannot be equally placed. You may hate to rate people, as I do, but it must be done regularly in our society, and in any society, which is not exactly equal at all points this must happen very often. You may as well realize this and learn to do the job more effectively than most people do—they simply make a choice and go on, rather than give the whole process a good deal of careful thought, as well as watching others doing it and learning from them.

6. There is another matter I mentioned in an earlier chapter and must now come back to. It is the rapidity with which the people respond to changes in a rating system. I told you how there was a constant battle between me and the users of the computer, me trying to optimize the performance for the system as a whole, and they trying to optimize their own use. Any change in the rating system you think will improve the system performance as a whole is apt to not work out well unless you have thought through the response of the individuals to the change—they will certainly change their behavior. You have only to think of your own optimization of your careers, of how changes in the rating system in the past have altered some of your plans and strategies.
7. Another thing which is obvious but seems necessary to mention; the popularity of a form of measurement has little relationship to its accuracy or relevance to the organization.
8. If the whole organization is working together to fool the top, there is little the top can do about it. When I was on a Board of Directors, I was so conscious of this I frequently came either a day early or else stayed a day late, and simply wandered around asking questions, looking, and asking myself if things were as reported. For example, once when inventory was very high, due to the change in the line of computers we were producing which forced us to have parts of both lines on hand at the same time, I walked along, suddenly turned towards the supply crib, and simply walked in. I then eyed things to decide if, in my own mind, there was any great discrepancy or were the reported amounts reasonably accurate… Again, were the computing machines we were supposed to be shipping actually on the loading dock, or were they mythical—as has happened in many a company? Nosing around I found at the end of each quarter the machines to be shipped were really shipped, but often by the process of scavenging the later machines

on the production line, and hence the next few weeks were spent in getting the scavenged machines back to proper state. I never could stop that bad habit of the employees, though I was on the Board of Directors! If you will but look around in your organization, you will find lots of strange things which really should not happen but are regarded as customary practice by the personnel.

9. "There is never time to do the job right, but there is always time to fix things later".
10. In computing, the programming effort is often measured by the number of lines of code—what easier measure is there? From the coder's point of view there is absolutely no reason to try to clean up a piece of code; quite the contrary, to get a higher rating on the productivity scale there is every reason to leave the excess instructions in there—indeed include a few "bells and whistles" if possible. That measure of software productivity, which is widely used, is one of the reasons why we have such bloated software systems these days. It is a counter incentive to the production the clean, compact, reliable coding we all want. Again, the measure used influences the result in ways which are detrimental to the whole system! It also establishes habits which at a later time are hard to remove.

You and Your Research

1. Why do I believe this talk is important? It is important because as far as I know each of you has but one life to lead, and it seems to me it is better to do significant things than to just get along through life to its end. Certainly, near the end it is nice to look back at a life of accomplishments rather than a life where you have merely survived and amused yourself. Thus, in a real sense I am preaching the message: (1) it is worth trying to accomplish the goals you set yourself, and (2) it is worth setting yourself high goals.
2. Having disposed of the psychological objections of luck and the lack of high IQ type brains, let us go on to how to do great things. Among the important properties to have is the belief you can do important things. If you do not work on important problems how can you expect to do important work? Yet, direct observation, and direct questioning of people, shows most scientists spend most of their time working on things they believe are not important nor are they likely to lead to important things. As an example, after I had been eating for some years with the Physics table at the Bell Telephone Laboratories restaurant, fame, promotion, and hiring by other companies ruined the average quality of the people so I shifted to the Chemistry table in another corner of the restaurant. I began by asking what the important problems were in chemistry, then later what important problems they were working on, and finally one day said, "If what you are working on is

not important and not likely to lead to important things, then why are you working on it?" After that I was not welcome and had to shift to eating with the Engineers! That was in the spring, and in the fall one of the chemists stopped me in the hall and said, "What you said caused me to think for the whole summer about what the important problems are in my field, and while I have not changed my research it was well worth the effort". I thanked him and went on—and noticed in a few months he was made head of the group. About 10 years ago I saw he became a member of the National Academy of Engineering. No other person at the table did I ever hear of, and no other person was capable of responding to the question I had asked, "Why are you not working on and thinking about the important problems in your area?" If you do not work on important problems, then it is obvious you have little chance of doing important things.

3. The courage to continue is essential since great research often has long periods with no success and many discouragements. The desire for excellence is an essential feature for doing great work. Without such a goal you will tend to wander like a drunken sailor. The sailor takes one step in one direction and the next in some independent direction. As a result, the steps tend to cancel each other, and the expected distance from the starting point is proportional to the square root of the number of steps taken. With a vision of excellence, and with the goal of doing significant work, there is tendency for the steps to go in the same direction and thus go a distance proportional to the number of steps taken, which in a lifetime is a large number indeed. As noted, before, chapter 1, the difference between having a vision and not having a vision, is almost everything, and doing excellent work provides a goal which is steady in this world of constant change.
4. One reason for this is fame in Science is a curse to quality productivity, though it tends to supply all the tools and freedom you want to do great things. Another reason is most famous people, sooner or later, tend to think they can only work on important problems—hence they fail to plant the little acorns which grow into the mighty oak trees. I have seen it many times, from Brattain of transistor fame and a Nobel Prize to Shannon and his Information Theory. Not that you should merely work on random things—but on small things which seem to you to have the possibility of future growth. In my opinion the Institute for Advanced Study at Princeton, N.J has ruined more great scientists than any other place has created—considering what they did before ore and what they did after going there. A few, like von Neumann, escaped the closed atmosphere of the place with all its physical comforts and prestige, and continued to contribute to the advancement of Science, but most remained there and continued to work on the same problems which got them there, but which were generally no longer of great importance to society. Thus, what you consider to be good working conditions may not be good for

you! There are many illustrations of this point. For example, working with one's door closed lets you get more work done per year than if you had an open door, but I have observed repeatedly later those with the closed doors, while working just as hard as others, seem to work on slightly the wrong problems, while those who have let their door stay open get less work done but tend to work on the right problems! I cannot prove the cause and effect relationship, I only observed the correlation. I suspect the open mind leads to the open door, and the open door tends to lead to the open mind; they reinforce each other.

5. After quite a few weeks of wondering what to do I finally said to myself, "Hamming, you believe machines can do symbol manipulation, why not get them to do the details of the programming?" Thus, I was led directly to a frontier of Computer Science by simply inverting the problem. What had seemed to be a defect now became an asset and pushed me in the right direction! Grace Hopper had a number of similar stories from Computer Science, and there are many other stories with the same moral: when stuck often inverting the problem, and realizing the new formulation is better, represents a significant step forward. I am not asserting all blockages can be so rearranged, but I am asserting many more than you might at first suspect can be so changed from a more or less routine response to a great one.
6. All these stories show the conditions you tend to want are seldom the best ones for you—the interaction with harsh reality tends to push you into significant discoveries which otherwise you would never have thought about while doing pure research in a vacuum of your private interests. Now to the matter of drive. Looking around you can easily observe great people have a great deal of drive to do things. I had worked with John Tukey for some years before I found he was essentially my age, so I went to our mutual boss and asked him, "How can anyone my age know as much as John Tukey does?" He leaned back, grinned, and said, "You would be surprised how much you would know if you had worked as hard as he has for as many years". There was nothing for me to do but slink out of his office, which I did. I thought about the remark for some weeks and decided, while I could never work as hard as John did, I could do a lot better than I had been doing. In a sense my boss was saying intellectual investment is like compound interest, the more you do the more you learn how to do, so the more you can do, etc. I do not know what compound interest rate to assign, but it must be well over 6%—one extra hour per day over a lifetime will much more than double the total output. The steady application of a bit more effort has a great total accumulation. But be careful—the race is not to the one who works hardest! You need to work on the right problem at the right time and in the right way—what I have been calling "style". At the

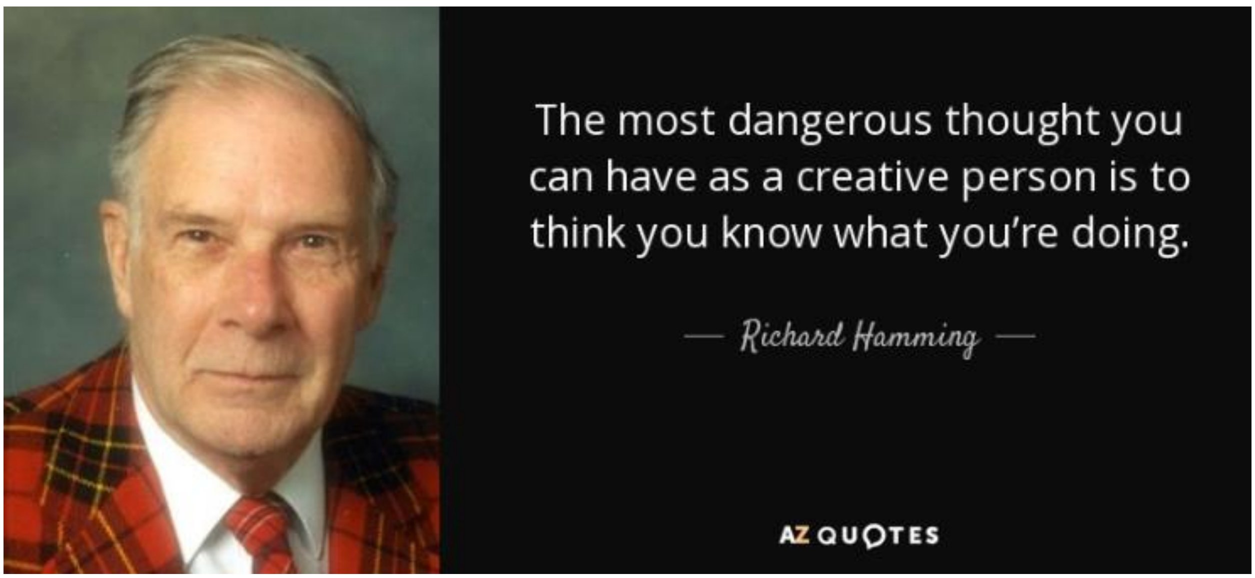
urging of others, for some years I set aside Friday afternoons for "great thoughts". Of course I would answer the telephone, sign a letter, and such trivia, but essentially, once lunch started, I would only think great thoughts—what was the nature of computing, how would it affect the development of science, what was the natural role of computers in Bell Telephone Laboratories, what effect will computers have on AT&T, on Science generally? I found it was well worth the 10% of my time to do this careful examination of where computing was heading so I would know where we were going and hence could go in the right direction. I was not the drunken sailor staggering around and canceling many of my steps by random other steps but could progress in a more or less straight line. I could also keep a sharp eye on the important problems and see that my major effort went to them. I strongly recommend this taking the time, on a regular basis, to ask the larger questions and not stay immersed in the sea of detail where almost everyone stays almost all of the time. These chapters have regularly stressed the bigger picture, and if you are to be leader into the future, rather than to be a follower of others, I am now saying it seems to me to be necessary for you to look at the bigger picture on a regular, frequent basis for many years.

7. There is another trait of great people I must talk about—and it took me a long time to realize it. Great people can tolerate ambiguity, they can both believe and disbelieve at the same time. You must be able to believe your organization and field of research is the best there is, but also there is much room for improvement! You can sort of see why this is a necessary trait If you believe too much you will not likely see the chances for significant improvements, you will see believe enough you will be filled with doubts and get very little chances for only the 2%, 5%, and 10% improvements; if you do not done. I have not the faintest idea of how to teach the tolerance of ambiguity, both belief and disbelief at the same time, but great people do it all the time.
8. Most great people also have 10 to 20 problems they regard as basic and of great importance, and which they currently do not know how to solve. They keep them in their mind, hoping to get a clue as to how to solve them. When a clue does appear, they generally drop other things and get to work immediately on the important problem. Therefore, they tend to come in first, and the others who come in later are soon forgotten. I must warn you however, the importance of the result is not the measure of the importance of the problem. The three problems in Physics, antigravity, teleportation, and time travel are seldom worked on because we have so few clues as to how to start—a problem is important partly because there is a possible attack on it, and not because of its inherent importance.

9. Again, you should do your job in such a fashion other can build on top of it. Do not in the process try to make yourself indispensable; if you do then you cannot be promoted because you will be the only one who can do what you are now doing! I have seen a number of times where this clinging to the exclusive rights to the idea has in the long run done much harm to the individual and to the organization. If you are to get recognition then others must use your results, adopt, adapt, extend, and elaborate them, and in the process give you credit for it. I have long held the attitude of telling everyone freely of my ideas, and in my long career I have had only one important idea "stolen" by another person. I have found people are remarkably honest if you are in your turn.
10. I must come to the topic of "selling" new ideas. You must master three things to do this (Chapter 5): 1. giving formal presentations, 2. producing written reports, 3. master the art of informal presentations as they happen to occur. All three are essential—you must learn to sell your ideas, not by propaganda, but by force of clear presentation. I am sorry to have to point this out; many scientists and others think good ideas will win out automatically and need not be carefully presented. They are wrong; many a good idea has had to be rediscovered because it was not well presented the first time, years before! New ideas are automatically resisted by the establishment, and to some extent justly. The organization cannot be in a continual state of ferment and change; but it should respond to significant changes. Change does not mean progress, but progress requires change.
11. Finally, I must address the topic of: is the effort required for excellent worth it? I believe it is—the chief gain is in the effort to change yourself, in the struggle with yourself, and it is less in the winning than you might expect. Yes, it is nice to end up where you wanted to be, but the person you are when you get there is far more important. I believe a life in which you do not try to extend yourself regularly is not worth living—but it is up to you to pick the goals you believe are worth striving for. As Socrates (470? -399) said, "The unexamined life is not worth living."

What I got out of it

1. This book is worth reading and re-reading but, unless you're really into math and science and some of the deep insights that can stem from reading through the formulas discussed within, I'd skip those sections and focus on the preface, orientation, creativity, experts, systems engineering, you get what you measure, and you and your research. I had come across the "You and Your Research" speech before and didn't realize it was part of a larger whole. With that context, this speech is that much better and, if nothing else, you should at least read that, print it, and re-read it every year.


The most dangerous thought you can have as a creative person is to think you know what you're doing.
— Richard Hamming —
AZ QUOTES