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A SCIENTIST'S LIFE

A Basis for an Evening Talk

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When I was first asked to give this talk, I thought of talking about your business, especially with a lot of jokes. But, on even slight thought that would be foolish - you already know more than I do in such areas!

What could I say that might be of interest to you? It finally came to me that I could talk on what it is to be a scientist, something that you might be interested in and on which I have some knowledge that you may not have. The rule of good writing is to write about what you know.

They say there are three kinds of people in this world, so they say: those who make things happen, those who watch things happen, and the vast majority who do not even know anything is happening. Our society has changed enormously within my lifetime, but few of my friends seem to be aware of how much and in what ways, nor do they seem to care!

Now science, and with it the engineering to translate science into action, is central to our society. You tend to take it for granted. During all my years at Bell Telephone Laboratories, when the power went out, I was amused to note how often people simply picked up the telephone and called in to complain. They took the telephone for granted! Yet, it is a very difficult thing to supply service to many people in a reliable fashion. The telephone business has a dis-economy of scale! When there are only three telephones the fourth requires just three interconnections to include it in the system. But when you have millions in service, each new phone must be connected, by some means or other, to all the existing ones! One sees a similar dis-economy of scale in public transportation in large cities.

There is a difference between politicians and scientists. Politicians are widely seen and often do very little for society; scientists tend not to be seen and they have transformed the society you live in.

What, then, is it to be one of those people you seldom see, but who have made, to a great extent, the world you live in? If I am to successfully communicate the answer to you, I need to talk in first person, not in vague terms of names like Newton, Galileo, Maxwell, Planck, Einstein, etc. Am I a great scientist? I suppose so. I have collected enough medals and honors, and the latest is a medal named after me with an annual prize of $10,000. I did not put up the money, as did Nobel for the Nobel Prizes; I only gave my name. It has taken a lot of years for me to realize clearly that I was one of those who did things in the world and had a hand in changing it. But when I think hard about it, I have to admit that I was a somebody, not just one who stood around and watched, cleaned up the details of new things, and wrote a lot of papers that were soon lost. Hence, I will take the liberty of talking about my own experiences as well as that of others that I have examined over the last 40 years during which I have studied what makes great science and great scientists.

Contrary to many people's beliefs, science is not easy to define. A glib version is that : "If you

know what you are doing then as a scientist you should not be doing it; in engineering it is the other way, if you do not know what you doing then you shouldn't be doing it!" The reality is that each does some of the other: of course, it is not black or white, but a matter of degree.

Science, as Einstein eloquently remarked, is a very lonely business. You know that you do not know what you are doing and you know that there is no answer in the back of the book! If there is to be an answer then you, and you alone, will have to find it. And, of course, you do not know that there is an answer at all!

Most people who fancy themselves as scientists cannot do this kind of lonely science! They cannot stand the loneliness of being out there in the unknown. Yes, they have lab smocks, and they often have the title, but still they are not up to the task. Instead they spend their lives working on safe corners of what has already been found, extending things, elaborating things, filling in small gaps. They spend their professional lives doing exercises that go slightly beyond what is already found in the book of knowledge.

The Wall Street Journal recently had an article on the discovery of high temperature (relatively speaking) super conductors at the IBM labs in Zurich. For some two and a half years, the scientists, who were considered fools, could not talk too much about the research to their friends. They had to conceal it from their management, and had to disguise what they were doing in the lab from visiting brass. They had no support except their own internal confidence that they knew that there was something out there when every other source was against their belief! It is a lonely business, and you only have to think of the price they would have paid had they failed!

I need to talk about one of my contributions, so let me turn to a brief discussion of it. It became clear to me in the mid 1940's that the computing machines we wanted to build would have many, many parts, and that the traditional design would be such that the isolated errors would limit the ability of the system. We simply cannot make things perfectly reliable, regardless of what you would like to think. In the telephone business, where I was then, having left Los Alamos and the design of atomic bombs at the end of the war, a single, isolated error will at worst give a single wrong number - in a computer it can ruin the whole computation!

What to do since we wanted big, reliable machines? We could, of course, build three and at various stages compare and take the majority vote. In such machines we would be able to correct any single error that occurred between the intercomparisons. So, it can be done. What I finally turned my mind to was, "What is the best possible design?" It is the method of encoding the information sent from one part of the machine to another so that at the receiving end the receiver can locate any single error and hence correct it. Indeed, I also supplied codes for not only correcting any single error, but at the same time detecting any pair of errors. And I sketched the elements of the general theory.

You see such codes not only in most computers, but also in the compact disc. I have tried to estimate what C. D.'s would cost to get onto the market without some such codes, (they use codes that have grown out of mine) and it seems that they would be at least three times as expensive if not ten times! With such codes, we can use poorer equipment and yet with a bit more effort get superior results by correcting the isolated errors that occur.

When I developed the codes and tried to publish them I ran against exactly that point. I was not allowed to say that we could build less expensive, poorer relays, and with a few more in the

design get better results. The company feared the lawyers who might seize on the statement that the system used inferior relays without understanding that for less total cost the performance was better through the underlying design.

The legal system is one of the curses that the scientist faces all the time. The legal system is pretty much designed to preserve the status quo - the scientist is working to change it. He runs head on into the law and the lawyer all the time, and as a result society does not have many of the things that could make life better. You are all familiar with one aspect of this in the drug business - the slowness of government regulation. They will not let a drug on the market lest it could cause harm, like thalidomide did. This delays drugs that could do good! It is the general opinion of those who think about such things that in this case the evil is the unwillingness to take risks. This means that progress is slowed down and that people whose lives could be saved by drugs find that they are not available on the American market. So if they have enough money, they go abroad for medical services!

Another difficulty that scientists have with lawyers is the difference in their basic approaches. The rule of science is cooperation - we are supposed to help each other to find the truth. Even in a case as I have one theory and you have a competing one and I find something that supports yours and condemns mine, I am supposed to go to you and tell you. I am not claiming that scientists are always this remarkable, but we do, in our sober moments remember the ideals and at times respond properly. I have been known to help others who were opposed to my beliefs! Thus science is based on the concept of cooperation - lawyers use confrontation! Now experience shows that cooperation is, in the long run, far more effective than confrontation. We find the lawyer's methods offensive and inefficient, but we are stuck with the legal system that is based on confrontation and not cooperation. The resulting inefficiency is getting justice (which they in no way pretend to deliver, they deliver only legalities.)

Internal management also supplies some brakes on research. It is probably good that some brakes be applied. We, as a society, simply do not have the resources to follow up on every promising idea. We must select and concentrate our efforts. In the process, a lot of slightly promising ideas that the inventor has great faith in must of necessity be abandoned. One has to learn to live with having promising ideas that are not followed through on. It is hard - almost like abandoning a newborn baby! Like a new born baby, a new idea that has not been developed has potentialities that are enormous. Who can say what the baby will grow up to be, and who can say what an undeveloped idea might become?

Returning to the idea of error correcting codes - I saw it linger, pretty much ignored by the company, for about ten years. Finally, the first electronic telephone office was built in Morris, Illinois and they were desperate and had to use it! Once in use, they could see the fact that I had maintained all along. The maintenance of the equipment was significantly easier because it told you where and when any part was failing - it could mark the spot almost exactly.

One hears a lot about the social responsibility of the scientist. Take the idea of error correcting codes for example. It is used now everywhere, throughout computers, space flights, sending pictures back to earth, in compact discs, in most medical gear that is at all complicated, etc. But could I, as the discoverer, have any idea of whether the future applications would be for good or evil? Hardly! Most of science is neutral with respect to the applications, it is the humans who put in the value judgement by the way they use the idea.

This same neutrality applies to almost all my contributions to science; one could not then, nor can say now, whether or not they will be used for more good than evil. It is nice to suppose that the scientist can know, but at the time of creation almost nothing can be known about the future use. It is like killing children at birth if you think they will grow up to be bad. Indeed, after almost 40 years one still cannot know future uses of the ability to build and maintain large electronic systems - for good or evil?

It is not that the scientist does not wonder and worry about the uses of his ideas, but that he cannot know and has little or no control over what other will do with it. Nor would you want it otherwise.

In teaching my classes I try to smuggle in a little of what it is to do great work - to inspire a few student into greatness. I have always observed that if you do not work on important problems, you are not likely to do important work. Most so called scientists spend all their lives working on "safe" problems - indeed, the government grant system encourages just that.

One cannot work only on important problems. History shows that it is while working on more mundane things that one notices the great things. I was using computers to get numerical results when I got to thinking about the problem of errors in large systems. I was also working on the early guided missiles at the same time and I thought of signalling through enemy jamming, signalling through "noise" as we say. The same codes do both things. To do great research one must involve themselves in small things and keep on eye out for the big things. All too often, fame causes the scientist to think that he should only work on important problems - and this tends to sterilize him! I have seen it repeatedly. One sees it in many of the Noble Prize winners - after they get the prize there is a noticable falling off of their productivity. They are too important in their own eyes!

Greatness seldom rests on a single discovery - rather the better scientists produce a stream of ideas over their life time. This brings up another hard part of the job - the letting go of a good idea before it is fully developed and getting back to the business of discovering another good idea. It is very hard to let go, but if you do not then you are not free to find the next one!

As I try to abstract out what is required of a scientist besides the ability to select what to work on and to find things, it is the ability to let go and get on. Many do not have that talent, and as a result the first good idea they get pulls them away from future greater discoveries they could make because they will not let go of the first. I have seen this all too often at all levels of scientific work. Of course there is the abandoning of an idea too soon, not carrying it our far enough, but the opposite effect is seldom seen by many. The failure to get on to the next idea that might be even greater a serious one! Yes, it is hard to let go in a field where you are the acknowledged expert and go back into the pond of scientists searching for another idea where you are again on the same level of recognition and respect.

The scientist is a funny animal. Although it is often said, and I have said it several times, the scientist selects the problem he works on, this is simply not true. It is far truer that the problem selects him! He finds that he must work on the problem - it has grabbed him. It is this emotional commitment to the problem that seems so essential to success. I have seen many very talented scientists who remain uncommitted as it were, and in their whole lifetime produced a stream of good things and completely missed greatness. The scientist must remain receptive to new ideas and allow them to take his life over - otherwise his life will be just good at best.

Greatness requires commitment in almost all fields.

You read in books and novels of the alienation of man from his world. This is because the literary people are alienated since they pride themselves on their ignorance of the technical basis of our society. Scientists seldom have this feeling of alienation. Theirs is the world that they have had a hand in building and in which they understand and feel they belong.

Having been in teaching now for 11 years, and having the leisure and in a sense the duty, to think about what things mean and what our world is about, I have come to the general feeling that the failure of the populace to learn simple mathematics is the basis of so much trouble. Galileo remarked that mathematics is the language of science (and of engineering too). If you do not speak, read, and understand the language you are an alien in our society. Yes, you live there, but you are one of those who must stand on the side and let it pass by without any real comprehension of what is happening.

Our era has been one the most exciting ones to live through. Space flight and the exploration of the solar system via space telescopes and radio telescopes on earth have been but a glamorous part. Lasers have made possible what was beyond belief a few years ago, especially in the medical profession. Lasers also make communication very different. You simply take it for granted due to your accepting the telephone, radio and TV as miracles beyond your understanding! Similarly, in computers both optical computing and the promise of super conducting computers promise whole new areas of exploration.

Computers are another big thing in our society. Most people take them as great data processing monsters that spit out crazy things at times. That they have already transformed the way science is done is hardly mentioned. Years ago I said in a speech to the President and Vice President of Bell Labs that then we did one out of ten experiments on the computer and the other nine in the lab, but that was before I left. I predicted that the ratio would be reversed and I was all too right. We now do most experiments by simulation on a computer to answer the question, "What if?" The underlying idea is not new, but the computer's capacity has transformed the areas in which we can ask, "What if?" Especially in areas where humans are involved, the computer is the only acceptable tool for experimentation.

I hope that I have given you some of the sense of excitement that the scientist, who participates in his society, feels. I have led a fabulous life in one of the most exciting eras of mankind - being a piece of the system that is transforming the conditions of human existence. We are but on the road, though the old motto of "the endless frontier" is not exactly accurate. The piling up of knowledge makes the frontier farther and farther from the starting point of the child and tends to discourage them from entering the race. We need to inspire more children to aim for greatness in the intellectual aspects of life. So far as I can see, this will require a sound grounding in mathematics for a long time.