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The future of science and engineering

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THE FUTURE OF SCIENCE AND ENGINEERING

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their future is in the Navy ... & future of the Navy tightly bound up as in engineering & science

Let me first say that I feel highly honored to be asked to give this talk.

It is said that there are more than one hundred ways of predicting the future, which suggests that most of them must not be very effective! The three obvious ways are: (1) study history, (2) use current trends, and (3) use your imagination. History tends not to repeat itself since the situation is never the same, but again it does tend to repeat because it is still the same humans who are creating history. Santayana said, "Those who can not remember the past are condemned to repeat it." It is perhaps an exaggeration, but does have an element of truth in it. The second tool, measuring current trends, is hard because the trend is essentially a difference over a short time and is hence very subject to small errors as well as local chance phenomena. The third tool, the use of the imagination, I have found to be the most valuable in the long run. If the method is to be at all effective one must think hard, reject one's first opinions, and struggle for basic clarity.

How far in the future am I thinking? A useful goal is the year 2020 - a time when some of you will be becoming Admirals and assuming the responsibility of the overall guidance of the Navy and of society generally. It is a convenient year because it suggests 2020 foresight! It is also convenient because I will not be around then to be told I was wrong!

All methods of predicting the future fail on the unexpected, the chance discovery. You

have only to think of my experiences in computing. I began at Los Alamos during the second World War helping compute the designs of proposed atomic bombs. We were using relay machines which had an average speed of less than one operation per second. It took three months around the clock to compute some of the problems - now they could be done in a few seconds! The relay computers were gradually replaced by vacuum tube machines, and while one could imagine (and it was happening) that the size of vacuum tubes and other components, as well as the voltages, would decrease, the idea of one million active components on a chip of the current sizes was beyond imagination! The invention of the transistor, and the subsequent development of the integrated circuit together has transformed the whole question of computers and their availability. They were not imaginable then. True, there were hints that solid state components would be increasingly used in computers; thus H. H. Aitken of Harvard was incorporating rectifiers as much as possible into his machines, but the very concept of an integrated circuit, which almost removed the terrible problem of soldered connections, among other things, was not imaginable then.

invention of integrated circuit impossible to imagine even by hindsight

If predicting the future is hard, there is nevertheless one well known rule. In the short term usually predictions are optimistic, but the long run they are pessimistic. The latter is true because one has trouble accepting the geometric growth of a field, that it builds exponentially on itself for a long time before saturation finally sets in. The first error, optimism, is more readily understood when you realize that the researcher must be optimistic to do any decent research at all!

as you find out when you write your thesis ... you don't get much done

It has been said that we are going through a "phase change" in science and engineering. You know what phase changes are when you go from ice to water, and water to vapor - the

material changes from one state to the other. In the process, say from ice to water, you add heat steadily and the temperature of the ice rises steadily until you reach 0° Centigrade whereupon the temperature stays the same until all the ice is converted to water - the latent heat of melting it is called - and then the temperature continues to rise. Similarly in the change of phase from water to steam there is the latent heat of vaporization.

put in energy w/o change in temperature...

The claim is that computers are creating a change of phase in the way we do science and engineering. It is taking time as we pass from the old way to the new way. Not too long ago we used experiments as the basic tool of exploration and occasionally used computing to check the experiments or to supply details that we could not easily measure in the experiment. For example, in fluid dynamics Euler long ago wrote down the fundamental equations and shortly afterwards others supplied the equations for some of the details. But the equations could not be solved is any useful form. Now we can, with the aid of computers, get many of the answers to the equations with their boundary conditions.

we have to change enormously how we do science

In the past in airplane design we used wind tunnels backed up by computers to supply some details; we now compute the design and use the wind tunnels as checks. In time we will use the wind tunnels less and less; we are passing into the age of computing the solutions to many of the equations that we believe we know, which describe the reality we are studying.

Thus the claim is that science is passing from one phase to another, that we are in the latent state of change, and it is hard to state clearly what the emerging state will be. Could it be that in time many of our theorems will be successfully encoded as compatible routines to be used in a flexible manner by computers directed by humans?

on computers ...
not looking at reality but figuring
out what it ought to be

It is also clear that as our society becomes more tightly integrated the "reach" of reliable prediction is shortening - more and more long term predictions about our society are less and less reliable.

If predicting the future is so difficult and faulty then why bother? There is a simple reason that is best explained in terms of the famous drunken sailor staggering around. With no clear goal he staggers this way and that way, often retracing his last step. As you know, this is called a "random walk" and you can expect that in n steps he will be a distance from where he started of about $n^{1/2}$. Of course, by chance he may be much farther, and by chance he may be near the starting point, but his expected distance will be about $n^{1/2}$ steps away from the start.

In the second version of the random walk there is a pretty girl over in the corner, and he tends to stagger in her direction. As a result at the end of n steps his distance tends to be proportional to n, though the coefficient of proportionality may be small.

Similarly, as you go through life making many, many small decisions every day, many more than one is apt to realize, the difference in how far you go is enormous whether you have a vision, (a distance proportional to the number of decisions), or have no vision of your future, (a distance proportional to the number of decision to the one half power). There are surely more than 10,000 decisions affecting your career, from the big obvious ones down to the way you dress on some occasion, from whether you goof off or study for an hour, etc, and the difference between 10,000 and 100 is a lot for any reasonable constant of proportionately.

Now it is a curious fact that for great scientists and engineers it does not seem to matter so much which goal you have, it is having a clear picture of yourself and where you are headed

that matters. For example, Michelson for whom this lecture series is named, back when he formed his ideas of what was important in science around the 1880's or earlier, felt keenly, as did many other scientists, that the future of science lay in the more precise measurement of physical constants. I do not want to belittle this attitude, since we have just seen the latest Noble prize given to three men for more accurate measurements, but you all know from your physics courses that right over the horizon of the new century was the complete turning over of the theoretical structure of physics, two theories of relativity as well as quantum mechanics - and Michelson really did not adjust to them but kept to his old vision! But he did great work and received a Nobel prize for it. The possession of a vision, with some suitable flexibility and not a monomanic vision of an exact narrow goal, is essential to great work - always admitting that there is an element of luck in all great work. But as Pasteur said, "Luck favors the prepared mind."

Since history is one of my main tools for predicting the future we need to look more closely at it. There were clues back in the late 1800's that all was not right in physics; indeed Michelson provided one of the great stumbling blocks with his failure to find the ether drift! There was also the failure of the black body radiation formula to fit reality in any fashion at all. Planck tried to derive a suitable formula to fit the data, and in one desperate trial he used the well known technique - derive it for finite discrete steps and then take the limit. He found that when he went to the limit the formula failed, but that at finite size it fit very well indeed. Thus out came Planck's constant!

Again, there was the matter of the radiation that ought to come from the electrons that were moving around the atom's center. Such radiation should be continuously emitted and gra-

dually bring the electron into the center! But of course the atoms were stable and emitted sharp lines of radiation.

There were a number of other disturbing effects that were known, but all of them tended to be ignored and brushed under the rug in the smug belief that essentially of all of physics was known and only more decimal places were needed.

Let us therefore look at the current situation in physics - which is one of the major bases of engineering. What troubles do we find?

Let us first look at what is called "the collapse of the wave function" in quantum mechanics. First we need to observe that the general theory of relativity says that useful signaling can not be done faster than the velocity of light. You can sort of see why this is - otherwise you could reach back and effect the past! The famous matter of killing your mother before you are born is but one example of the theoretical consequences of time travel into the past.

To explain in simple words what the "collapse of the wave function" is, consider light coming into a telescope. From your physics you think of a wave front that enters the tube of the telescope as an entire wave. And this impression is strengthened by the fact that the small diffractions effects that you can see depend directly on the diameter of the telescope. Thus in some sense the incoming light knows the size of the telescope aperture. And if there is a small mirror in the center to reflect the light down the tube again then the fine spider web supports produce further diffraction effects that depend directly on the pattern of the supports that interfere with the clear entry of the telescope tube.

So, somehow, the light "senses" the larger structure of the telescope, but you also know

that on the photographic plate all the energy of the incoming quantum of light goes to developing one grain on the plate, or being recorded by whatever detector the telescope is using. Thus what was apparently spread out everywhere, collapses into a single point, almost. The diffraction pattern gives, as it were, a probability distribution of where the photons are going to hit, but each photon independently must hit in a single place. This is the famous wave-particle duality of quantum mechanics, and the professor is forced, after trying to explain it as best he can if honest, to say, "I really cannot explain it - you will get used to it!"

Well, Alain Aspect in Paris has done experiments that bear on the speed of collapse - which the quantum mechanics theory seemed to indicate was instantaneous. He sent out two particles with opposite spin and in opposite directions. After they were well apart he set one measuring device, at random, to measure the spin of one particle. As you know in quantum mechanics it is thought (in the Copenhagen interpretation) that before measurement the particle is not in any one definite state. The random measurement puts the particle in some state. He then measured the state of the other particle and found a definite correlation. It would appear that the act of measuring one particle was immediately communicated to the other particle - thus providing a way of signaling that clearly violates a cherished principle of general relativity. It is troubling to say the least!

Another item that you must be aware of from your studies is the repeated experiments to measure gravity waves which should occur. With increasingly more accurate measuring instruments one would have expected that long ago we would have found gravity waves but apparently, if they exist, they are too small or are much weaker than are expected. - too small for the current theory!

Still another troubling detail is our failure, so far, to find the "top quark" which our theories strongly indicate should be there and we should have found it before now.

Another disturbing feature is that whatever the probability is that occurs in quantum mechanics it is clearly *not* the probability that is taught in the conventional math courses where one uses real numbers - probability is measured by a real number between 0 and 1 - while quantum mechanics clearly uses complex numbers for the wave functions and on combining them there is the possibility of interference!

In cosmology it is assumed that red shift arises only from the Doppler effect, yet well respected astronomers have produced strong evidence that there must be other causes of the red shift.

Again, in cosmology, the big bang theory suggests a great deal of homogeneity in the universe, but we are finding a lot of detailed structure which may be of too large a size to fit in conveniently to the current theories of the origin of the universe. And at the moment some distant *quasars* seem to be too evolved for what we think is the time they have existed. We also *seem* not to be able to see about 90% of the matter producing gravitational effects in the universe! We are missing about 90% of the universe!

Thus the situation in theoretical physics at the turn of this century is not so different from that at the turn of the last century. Does this mean that we are to expect a similar creation of startling new theories? Does history inevitable repeat? Or will this not occur? Will they be explained away within our current theories, or will they remain unexplained?

Add to this the simple fact that you well know that science and engineering are

progressing at an exponential rate - in the number of people, in results, and in complications. Science has done this at a rate of about doubling every 17 years since the time of Newton - say 1687, the date of publication of his Principa. But our minds are not significantly better than the minds of that period. We have managed to handle the expansion of science by one simple device - specialization. Where Newton knew much of the the current natural science, we now specialize very highly. I recently attended a conference devoted to the single topic of testing integrated circuit chips!

we are not smarter than Newton we have coped with it (increases in knowledge) by specialization

If this doubling trend were to continue for 340 years, 20 doubling periods, then for each field of specialization that we now have we would have a million! You know in your hearts that that is not going to happen! We are at a period in the evolution of science where things must change in the near future, yet almost no scientist cares to think about the latter! Nor any engineer! We refuse to face the consequences of our rapid piling up of knowledge. Computers can only partially rescue us.

analogy if you want a baby in one month you put 9 women on the job

Another aspect of modern science and engineering is that in the immediate past the two fields attracted a disproportionate fraction of the best minds in our society. Currently that is no longer true! *If* you subscribe to the "great man" theory, that the few create and lead, and that the majority are in a sense the janitors of their field, then progress will slow down. If you think that the great advances in the future can be done by masses of smaller people then the future you see is different from that which you project from the great man theory. We see a strong trend to "big science". How will the "loner" survive in the future? How well can we get along without great leaders?

Vannevar Bush popularized the saying, "Science, the endless frontier." But is it? Is

there an infinite amount or is there only a finite amount of fundamental knowledge, and if finite how close are we to that now? Which view you take has a great effect on your projections of the future. It is simply *not* obvious that there is an infinite amount of fundamentals to be learned - and if there is then it tends to discourage one. Sort of like computing more digits of the number pi when we already have over a billion digits. Yes, in a sense each new digit is new information - but is that a reasonable definition of "information"? Is it progress to go on that way, getting more and more digits and more and more details? Is that the future of science and engineering you project? It raises the terrible question which in a sense you answer each day by how you act, "What knowledge is worth knowing"?

There are sounds that you cannot hear but that some animals, such as dogs, can hear. There are tastes similarly that you cannot taste, and sights you cannot see, being limited to about one octave of the electromagnetic spectrum. These limitations come from the sense organs you have and not from the source. Since this is true then why not unthinkable thoughts - thoughts that you cannot think, given the way your mind is wired? Why should we blandly assume that we can think anything? Indeed, quantum mechanics and the wave-particle duality may be one of these unthinkable thoughts! More than 50 years of teaching the topic and, as I said before, the professor is reduced to saying "I cannot explain it - you will get used to it."

But quantum mechanics is also a possible clue to the future - even if we cannot think about the subject we can develop a mathematical framework that we can use to successfully predict things! Unthinkable thoughts, if they exist, need not completely block us; we can construct a formalism that will carry us partly forward.

I suppose you have heard of Gödel's theorems that say, more or less, that in any

reasonably rich field of mathematics there are, apparently, theorems whose truth or falsity cannot be proved within the system. Now this is not really a theorem about mathematics, it is a theorem about the limitations of the method of using symbols! It says that there are definite limitations on formal systems of symbols. Again, this does not mean that we cannot make further progress even in the forbidden directions, but that we must then resort to other than formal symbolic methods

Gödel's theorems suggest such questions as: can there be physical theories to explain any set of data? We have not yet formalized just what we will accept as the meaning of the word "theory", so we cannot prove a similar type of theorem, but one suspects that once we do define "theory" then we will find definite limitations on what theories can explain, and clues to what they cannot explain.

These are some of the possible limitations on the future, which I am conveniently taking as up to the year 2020. These are, in a sense, some limitations on the *possibilities* of the future. Looking back 30 years to 1960 shows you how much change has happened; we should see more than that in the next 30 years!

But the future is not just what might happen. You need also to look at what *can* happen, and this depends on the surrounding society. I propose to use the word "bureaucracy" to refer to the social system. The word is generally used in a derogatory way, but you need to realize what it is. If each person "does their thing", as the saying goes, then you have a mob. One of the main purposes of the bureaucracy is to provide direction to the isolated efforts, so that the whole is more than the sum of the parts - to convert the mob into an army.

Bureaucracy gets its bad reputation from a number of features. One is the diffusion of responsibility. No one is responsible for a bad decision - you are told that is the rule and so that is that. You cannot pin the idiocy on any one individual! But we are all like that. Most professors, for example, will produce a formula combining homework, quiz grades, midterm, and final exam grade for the course grade. This is simply hiding behind a bureaucratic device rather than be willing to carefully consider each student on their own merits, to judge the individual as an individual rather than apply an arbitrary formula for measuring the student. I need not belabor the point - you see both the evil and the necessity of some sort of bureaucratic method for dealing with a large number of individual cases.

A second bad feature of bureaucracy is that it tends to respond to isolated crises with no overall direction. Each minor crisis tends to produce a new rule to prevent or handle such situations in the future. However, at times bureaucracy does pull itself together and look at the situation in the large. For example, I hear that at present the procurement process is so unwieldy that there is a serious effort to look at the whole as a whole and not as a sequence of minor crisis as the system developed in the past. Occasionally we also have large scale attempts to reduce the paper handling that bureaucracies tend to produce.

A well experienced friend of mine remarked that bureaucracy seems to go with civilization! You can't have one without the other. Bureaucracy is not all evil, it is a necessary tool for civilization that is both good and evil. It tries to be fair and treat everyone the same. Which is something we want for others. No special privileges for them that we do not get - but of course *we* want to be treated on our own merits, and not by a formula!

Up to now I have been talking about what is possible in the future of science and

1. what is possible ?
2. what is probable ?
3. what should be ?

engineering. Now I am talking about what is *likely* to happen when these possibilities are modified and filtered though the existing and future bureaucracies. If you do not recognize these limitation then your predictions will probably be very wrong! Thus in predicting the future you must also ask what is *likely* to happen?

Finally, I have learned to also ask, "What do you wish would happen? What do you believe the US Navy should be in the year 2020?" I will not presume to tell you any answers to this question - it is up to you as professionals to decide. You should spend a great deal of time and effort on this question if you want to have a direction to your future and not have a drunken sailor career.

I now point out that in so far as what you think *can* happen, and again in so far as it differs from what you think *will* probably happen, and again in so far as it differs from what you *want* to happen, then you have the possibility of becoming one of those who make the right things happen rather than enduring the obvious future. It is in the understanding of what *can*, *probably will*, and *should* happen that lets you see how to increase the latter probabilities. And in the process you become part of history!

Now the idea that you can be part of history seems alien to most young people, but let me assure you that indeed some of you can become a part of history, not just a name in a long graduation list, or on a promotion list, or just a footnote in history, but some of you may provide the material from which future histories are written. In my life I have found I became a part of history, and am likely to remain in text books for some time. Of course, in the fullness of time almost everything will fade - if our society lasts a million years even Issac Newton's name will probably be lost. But even if fame is temporary still it is a pleasant feeling that you have made

the world a better place to live in.

I have indicated that, insofar as I have seen, those who make a difference tend to be those who have a vision of the future - they walk the farthest. Thus I came here to give this talk mainly to try to get some of you to systematically think of the future; yours, the Navy's, your country's, and of the whole civilization in which you live. Without a vision it is doubtful that you will matter much in history.

I have often said that there are three kinds of people; those who do things, those who stand around and watch, and the vast majority who do not even know anything is happening. Why should you struggle to be one of the first group? It is in the struggle that you make of yourself something worth being. And I trust that you see the necessity of having a vision of the future, yours, the Navy's, your country's and even society's. You have all these obligations. All of you have the initial abilities to matter, or else you would not be here, you are getting the education to equip you to do important things, and I hope I have opened your eyes to the necessity of having a vision of your future so that your many, many small steps will add up to a great career. We will have a great need for great officers in the uncertain future. I trust that some of you will meet the challenge. Thank you for listening to my preaching on the topic of making something of yourself via finding your own vision of your future.

those who have a vision of the future walk the farthest