

The Uncertainty of Science

I WANT TO ADDRESS myself directly to the impact of science on man's ideas in other fields, a subject Mr. John Danz particularly wanted to be discussed. In the first of these lectures I will talk about the nature of science and emphasize particularly the existence of doubt and uncertainty. In the second lecture I will discuss the impact of scientific views on political questions, in particular the question of national enemies, and on religious questions. And in the third lecture I will describe how society looks to me—I could say how society looks to a scientific man, but it is only how it looks to me—and what future scientific discoveries may produce in terms of social problems.

What do I know of religion and politics? Several friends in the physics departments here and in other places laughed and said, "I'd like to come and hear what you have to say. I never knew you were interested very much in those things." They mean, of course, I am interested, but I would not dare to talk about them.

In talking about the impact of ideas in one field on ideas in another field, one is always apt to make a fool of oneself. In these days of specialization there are too few people who have such a deep understanding of two departments of our knowledge that they do not make fools of themselves in one or the other.

The ideas I wish to describe are old ideas. There is practically nothing that I am going to say tonight that could not easily have been said by philosophers of the seventeenth century. Why repeat all this? Because there are new generations born every day. Because there are great ideas developed in the history of man, and these ideas do not last unless they are passed purposely and clearly from generation to generation.

Many old ideas have become such common knowledge that it is not necessary to talk about or explain them again. But the ideas associated with the problems of the development of science, as far as I can see by looking around me, are not of the kind that everyone appreciates. It is true that a large number of people do appreciate them. And in a university particularly most people appreciate them, and you may be the wrong audience for me.

Now in this difficult business of talking about the impact of the ideas of one field on those of another, I shall start at the end that I know. I do know about science. I know its ideas and its methods, its attitudes toward knowledge, the sources of its progress, its mental discipline. And therefore, in this first lecture, I shall talk about the science that I know, and I shall leave the more ridiculous of my statements for the next two lectures, at which, I assume, the general law is that the audiences will be smaller.

What is science? The word is usually used to mean one of three things, or a mixture of them. I do not think we need to be precise—it is not always a good idea to be too precise. Science means, sometimes, a special method of finding things out. Sometimes it means the body of knowledge arising from the things found out. It may also mean the new things you can do when you have found something out, or the actual doing of new things. This last field is usually called technology—but if you look at the science section in Time magazine you will find it covers about 50 percent what new things are found out and about 50 percent what new things can be and are being done. And so the popular definition of science is partly technology, too.

I want to discuss these three aspects of science in reverse order. I will begin with the new things that you can do—that is, with technology. The most obvious characteristic of science is its application, the fact that as a consequence of science one has a power to do things. And the effect this power has had need hardly be mentioned. The whole industrial revolution would almost have been impossible without the development of science. The possibilities today of producing quantities of food adequate for such a large population, of controlling sickness—the very fact that there can be free men without the necessity of slavery for full production—are very likely the result of the development of scientific means of production.

Now this power to do things carries with it no instructions on how to use it, whether to use it for good or for evil. The product of this power is either good or evil, depending on how it is used. We like improved production, but we have problems with automation. We are happy with the development of medicine, and then we worry about the number of births and the fact that no one dies from the diseases we have eliminated. Or else, with the same knowledge of bacteria, we have hidden laboratories in which men are working as hard as they can to develop bacteria for which no one else will be able to find a cure. We are happy with the development of air transportation and are impressed by the great airplanes, but we are aware also of the severe horrors of air war. We are pleased by the ability to communicate between nations, and then we worry about the fact that we can be snooped upon so easily. We are excited by the fact that space can now be entered; well, we will undoubtedly have a difficulty there, too. The most famous of all these imbalances is the development of nuclear energy and its obvious problems.

Is science of any value?

I think a power to do something is of value. Whether the result is a good thing or a bad thing depends on how it is used, but the power is a value.

Once in Hawaii I was taken to see a Buddhist temple. In the temple a man said, "I am going to tell you something that you will never forget." And then he said, "To every man is given the key to the gates of heaven. The same key opens the gates of hell."

And so it is with science. In a way it is a key to the gates of heaven, and the same key opens the gates of hell, and we do not have any instructions as to which is which gate. Shall we throw away the key and never have a way to enter the gates of heaven? Or shall we struggle with the problem of which is the best way to use the key? That is, of course, a very serious question, but I think that we cannot deny the value of the key to the gates of heaven.

All the major problems of the relations between society and science lie in this same area. When the scientist is told that he must be more responsible for his effects on society, it is the applications of science that are referred to. If you work to develop nuclear energy you must realize also that it can be used harmfully. Therefore, you would expect that, in a discussion of this kind by a scientist, this would be the most important topic. But I will not talk about it further. I think that to say these are scientific problems is an exaggeration. They are far more humanitarian problems. The fact that how to work the power is clear, but how to control it is not, is something not so scientific and is not something that the scientist knows so much about.

Let me illustrate why I do not want to talk about this. Some time ago, in about 1949 or 1950, I went to Brazil to teach physics. There was a Point Four program in those days, which was very exciting—everyone was going to help the underdeveloped countries. What they needed, of course, was technical know-how.

In Brazil I lived in the city of Rio. In Rio there are hills on which are homes made with broken pieces of wood from old signs and so forth. The people are extremely poor. They have no sewers and no water. In order to get water they carry old gasoline cans on their heads down the hills. They go to a place where a new building is being built, because there they have water for mixing cement. The people fill their cans

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with water and carry them up the hills. And later you see the water dripping down the hill in dirty sewage. It is a pitiful thing.

Right next to these hills are the exciting buildings of the Copacabana beach, beautiful apartments, and so on.

And I said to my friends in the Point Four program, "Is this a problem of technical know-how? They don't know how to put a pipe up the hill? They don't know how to put a pipe to the top of the hill so that the people can at least walk uphill with the empty cans and downhill with the full cans?"

So it is not a problem of technical know-how. Certainly not, because in the neighboring apartment buildings there are pipes, and there are pumps. We realize that now. Now we think it is a problem of economic assistance, and we do not know whether that really works or not. And the question of how much it costs to put a pipe and a pump to the top of each of the hills is not one that seems worth discussing, to me.

Although we do not know how to solve the problem, I would like to point out that we tried two things, technical know-how and economic assistance. We are discouraged with them both, and we are trying something else. As you will see later, I find this encouraging. I think that to keep trying new solutions is the way to do everything.

Those, then are the practical aspects of science, the new things that you can do. They are so obvious that we do not need to speak about them further.

The next aspect of science is its contents, the things that have been found out. This is the yield. This is the gold. This is the excitement, the pay you get for all the disciplined thinking and hard work. The work is not done for the sake of an application. It is done for the excitement of what is found out. Perhaps most of you know this. But to those of you who do not know it, it is almost impossible for me to convey in a lecture this important aspect, this exciting part, the real reason for science. And without understanding this you miss the whole point. You cannot understand science and its relation to anything else unless you understand and appreciate the great adventure of our time. You do not live in your time unless you understand that this is a tremendous adventure and a wild and exciting thing.

Do you think it is dull? It isn't. It is most difficult to convey, but perhaps I can give some idea of it. Let me start anywhere, with any idea.

For instance, the ancients believed that the earth was the back of an elephant that stood on a tortoise that swam in a bottomless sea. Of course, what held up the sea was another question. They did not know the answer.

The belief of the ancients was the result of imagination. It was a poetic and beautiful idea. Look at the way we see it today. Is that a dull idea? The world is a spinning ball, and people are held on it on all sides, some of them upside down. And we turn like a spit in front of a great fire. We whirl around the sun. That is more romantic, more exciting. And what holds us? The force of gravitation, which is not only a thing of the earth but is the thing that makes the earth round in the first place, holds the sun together and keeps us running around the sun in our perpetual attempt to stay away. This gravity holds its sway not only on the stars but between the stars; it holds them in the great galaxies for miles and miles in all directions.

This universe has been described by many, but it just goes on, with its edge as unknown as the bottom of the bottomless sea of the other idea—just as mysterious, just as awe-inspiring, and just as incomplete as the poetic pictures that came before.

But see that the imagination of nature is far, far greater than the imagination of man. No one who did not have some inkling of this through observations could ever have imagined such a marvel as nature is.

Or the earth and time. Have you read anywhere, by any poet, anything about time that compares with real time, with the long, slow process of evolution? Nay, I went too quickly. First, there was the earth without anything alive on it. For billions of years this ball was spinning with its sunsets and its waves and the sea and the noises, and there was no thing alive to appreciate it. Can you conceive, can you appreciate or fit into your ideas what can be the meaning of a world without a living thing on it? We are so used to looking at the world from the point of view of living things that we cannot understand what it means not to be alive, and yet most of the time the world had nothing alive on it. And in most places in the universe today there probably is nothing alive.

Or life itself. The internal machinery of life, the chemistry of the parts, is something beautiful. And it turns out that all life is interconnected with all other life. There is a part of chlorophyll, an important chemical in the oxygen processes in plants, that has a kind of square pattern; it is a rather pretty ring called a benzene ring. And far removed from the plants are animals like ourselves, and in our oxygen-containing systems, in the blood, the hemoglobin, there are the same interesting and peculiar square rings. There is iron in the center of them instead of magnesium, so they are not green but red, but they are the same rings.

The proteins of bacteria and the proteins of humans are the same. In fact it has recently been found that the protein-making machinery in the bacteria can be given orders from material from the red cells to produce red cell proteins. So close is life to life. The universality of the deep chemistry of living things is indeed a fantastic and beautiful thing. And all the time we human beings have been too proud even to recognize our kinship with the animals.

Or there are the atoms. Beautiful - mile upon mile of one ball after another ball in some repeating pattern in a crystal. Things that look quiet and still, like a glass of water with a covered top that has been sitting for several days, are active all the time; the atoms are leaving the surface, bouncing around inside, and coming back. What looks still to our crude eyes is a wild and dynamic dance.

And, again, it has been discovered that all the world is made of the same atoms, that the stars are of the same stuff as ourselves. It then becomes a question of where our stuff came from. Not just where did life come from, or where did the earth come from, but where did the stuff of life and of the earth come from? It looks as if it was belched from some exploding star, much as some of the stars are exploding now. So this piece of dirt waits four and a half billion years and evolves and changes, and now a strange creature stands here with instruments and talks to the strange creatures in the audience. What a wonderful world!

Or take the physiology of human beings. It makes no difference what I talk about. If you look closely enough at anything, you will see that there is nothing more exciting than the truth, the pay dirt of the scientist, discovered by his painstaking efforts.

In physiology you can think of pumping blood, the exciting movements of a girl jumping a jump rope. What goes on inside? The blood pumping, the interconnecting nerves—how quickly the influences of the muscle nerves feed right back to the brain to say, "Now we have touched the ground, now increase the tension so I do not hurt the heels." And as the girl dances up and down, there is another set of muscles that is fed from another set of nerves that says, "One, two, three, O'Leary, one, two, ..." And while she does that, perhaps she smiles at the professor of physiology who is watching her. That is involved, too!

And then electricity The forces of attraction, of plus and minus, are so strong that in any normal substance all the plusses and minuses are carefully balanced out, everything pulled together with everything else. For a long time no one even noticed the phenomenon of electricity, except once in a while when they rubbed a piece of amber and it attracted a piece of paper. And yet today we find, by playing with these things, that we have a tremendous amount of machinery inside. Yet science is still not thoroughly appreciated.

To give an example, I read Faraday's Chemical History of a Candle, a set of six Christmas lectures for children. The point of Faraday's lectures was that no matter what you look at, if you look at it closely

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enough, you are involved in the entire universe. And so he got, by looking at every feature of the candle, into combustion, chemistry, etc. But the introduction of the book, in describing Faraday's life and some of his discoveries, explained that he had discovered that the amount of electricity necessary to perform electrolysis of chemical substances is proportional to the number of atoms which are separated divided by the valence. It further explained that the principles he discovered are used today in chrome plating and the anodic coloring of aluminum, as well as in dozens of other industrial applications. I do not like that statement. Here is what Faraday said about his own discovery: "The atoms of matter are in some ways endowed or associated with electrical powers, to which they owe their most striking qualities, amongst them their mutual chemical affinity." He had discovered that the thing that determined how the atoms went together, the thing that determined the combinations of iron and oxygen which make iron oxide is that some of them are electrically plus and some of them are electrically minus, and they attract each other in definite proportions. He also discovered that electricity comes in units, in atoms. Both were important discoveries, but most exciting was that this was one of the most dramatic moments in the history of science, one of those rare moments when two great fields come together and are unified. He suddenly found that two apparently different things were different aspects of the same thing. Electricity was being studied, and chemistry was being studied. Suddenly they were two aspects of the same thing—chemical changes with the results of electrical forces. And they are still understood that way. So to say merely that the principles are used in chrome plating is inexcusable.

And the newspapers, as you know, have a standard line for every discovery made in physiology today: "The discoverer said that the discovery may have uses in the cure of cancer." But they cannot explain the value of the thing itself.

Trying to understand the way nature works involves a most terrible test of human reasoning ability. It involves subtle trickery, beautiful tightropes of logic on which one has to walk in order not to make a mistake in predicting what will happen. The quantum mechanical and the relativity ideas are examples of this.

The third aspect of my subject is that of science as a method of finding things out. This method is based on the principle that observation is the judge of whether something is so or not. All other aspects and characteristics of science can be understood directly when we understand that observation is the ultimate and final judge of the truth of an idea. But "prove" used in this way really means "test," in the same way that a hundred-proof alcohol is a test of the alcohol, and for people today the idea really should be translated as, "The exception tests the rule." Or, put another way, "The exception proves that the rule is wrong." That is the principle of science. If there is an exception to any rule, and if it can be proved by observation, that rule is wrong.

The exceptions to any rule are most interesting in themselves, for they show us that the old rule is wrong. And it is most exciting, then, to find out what the right rule, if any, is. The exception is studied, along with other conditions that produce similar effects. The scientist tries to find more exceptions and to determine the characteristics of the exceptions, a process that is continually exciting as it develops. He does not try to avoid showing that the rules are wrong; there is progress and excitement in the exact opposite. He tries to prove himself wrong as quickly as possible.

The principle that observation is the judge imposes a severe limitation to the kind of questions that can be answered. They are limited to questions that you can put this way: "if I do this, what will happen?" There are ways to try it and see. Questions like, "should I do this?" and "what is the value of this?" are not of the same kind.

But if a thing is not scientific, if it cannot be subjected to the test of observation, this does not mean that it is dead, or wrong, or stupid. We are not trying to argue that science is somehow good and other things are somehow not good. Scientists take all those things that can be analyzed by observation, and thus the things called science are found out. But there are some things left out, for which the method does not work. This does not mean that those things are unimportant. They are, in fact, in many ways the most important. In any decision for action, when you have to make up your mind what to do, there is always a "should" involved, and this cannot be worked out from "if I do this, what will happen?" alone. You say,

"Sure, you see what will happen, and then you decide whether you want it to happen or not." But that is the step the scientist cannot take. You can figure out what is going to happen, but then you have to decide whether you like it that way or not.

There are in science a number of technical consequences that follow from the principle of observation as judge. For example, the observation cannot be rough. You have to be very careful. There may have been a piece of dirt in the apparatus that made the color change; it was not what you thought. You have to check the observations very carefully, and then recheck them, to be sure that you understand what all the conditions are and that you did not misinterpret what you did.

It is interesting that this thoroughness, which is a virtue, is often misunderstood. When someone says a thing has been done scientifically, often all he means is that it has been done thoroughly. I have heard people talk of the "scientific" extermination of the Jews in Germany. There was nothing scientific about it. It was only thorough. There was no question of making observations and then checking them in order to determine something. In that sense, there were "scientific" exterminations of people in Roman times and in other periods when science was not so far developed as it is today and not much attention was paid to observation. In such cases, people should say "thorough" or "thoroughgoing," instead of "scientific."

There are a number of special techniques associated with the game of making observations, and much of what is called the philosophy of science is concerned with a discussion of these techniques. The interpretation of a result is an example. To take a trivial instance, there is a famous joke about a man who complains to a friend of a mysterious phenomenon. The white horses on his farm eat more than the black horses. He worries about this and cannot understand it, until his friend suggests that maybe he has more white horses than black ones.

It sounds ridiculous, but think how many times similar mistakes are made in judgments of various kinds. You say, "My sister had a cold, and in two weeks ..." It is one of those cases, if you think about it, in which there were more white horses. Scientific reasoning requires a certain discipline, and we should try to teach this discipline, because even on the lowest level such errors are unnecessary today.

Another important characteristic of science is its objectivity. It is necessary to look at the results of observation objectively, because you, the experimenter, might like one result better than another. You perform the experiment several times, and because of irregularities, like pieces of dirt falling in, the result varies from time to time. You do not have everything under control. You like the result to be a certain way, so the times it comes out that way, you say, "See, it comes out this particular way." The next time you do the experiment it comes out different. Maybe there was a piece of dirt in it the first time, but you ignore it.

These things seem obvious, but people do not pay enough attention to them in deciding scientific questions or questions on the periphery of science. There could be a certain amount of sense, for example, in the way you analyze the question of whether stocks went up or down because of what the President said or did not say.

Another very important technical point is that the more specific a rule is, the more interesting it is. The more definite the statement, the more interesting it is to test. If someone were to propose that the planets go around the sun because all planet matter has a kind of tendency for movement, a kind of motility, let us call it an "oomph," this theory could explain a number of other phenomena as well. So this is a good theory, is it not? No. It is nowhere near as good as a proposition that the planets move around the sun under the influence of a central force which varies exactly inversely as the square of the distance from the center. The second theory is better because it is so specific; it is so obviously unlikely to be the result of chance. It is so definite that the barest error in the movement can show that it is wrong; but the planets could wobble all over the place, and, according to the first theory, you could say, "Well, that is the funny behavior of the 'oomph.'"

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So the more specific the rule, the more powerful it is, the more liable it is to exceptions, and the more interesting and valuable it is to check.

Words can be meaningless. If they are used in such a way that no sharp conclusions can be drawn, as in my example of "oomph," then the proposition they state is almost meaningless, because you can explain almost anything by the assertion that things have a tendency to motility. A great deal has been made of this by philosophers, who say that words must be defined extremely precisely. Actually, I disagree somewhat with this; I think that extreme precision of definition is often not worthwhile, and sometimes it is not possible—in fact mostly it is not possible, but I will not get into that argument here.

Most of what many philosophers say about science is really on the technical aspects involved in trying to make sure the method works pretty well. Whether these technical points would be useful in a field in which observation is not the judge I have no idea. I am not going to say that everything has to be done the same way when a method of testing different from observation is used. In a different field perhaps it is not so important to be careful of the meaning of words or that the rules be specific, and so on. I do not know.

In all of this I have left out something very important. I said that observation is the judge of the truth of an idea. But where does the idea come from? The rapid progress and development of science requires that human beings invent something to test.

It was thought in the Middle Ages that people simply make many observations, and the observations themselves suggest the laws. But it does not work that way. It takes much more imagination than that. So the next thing we have to talk about is where the new ideas come from. Actually, it does not make any difference, as long as they come. We have a way of checking whether an idea is correct or not that has nothing to do with where it came from. We simply test it against observation. So in science we are not interested in where an idea comes from.

There is no authority who decides what is a good idea. We have lost the need to go to an authority to find out whether an idea is true or not. We can read an authority and let him suggest something; we can try it out and find out if it is true or not. If it is not true, so much the worse— so the "authorities" lose some of their "authority."

The relations among scientists were at first very argumentative, as they are among most people. This was true in the early days of physics, for example. But in physics today the relations are extremely good. A scientific argument is likely to involve a great deal of laughter and uncertainty on both sides, with both sides thinking up experiments and offering to bet on the outcome. In physics there are so many accumulated observations that it is almost impossible to think of a new idea which is different from all the ideas that have been thought of before and yet that agrees with all the observations that have already been made. And so if you get anything new from anyone, anywhere, you welcome it, and you do not argue about why the other person says it is so.

Many sciences have not developed this far, and the situation is the way it was in the early days of physics, when there was a lot of arguing because there were not so many observations. I bring this up because it is interesting that human relationships, if there is an independent way of judging truth, can become unargumentative.

Most people find it surprising that in science there is no interest in the background of the author of an idea or in his motive in expounding it. You listen, and if it sounds like a thing worth trying, a thing that could be tried, is different, and is not obviously contrary to something observed before, it gets exciting and worthwhile. You do not have to worry about how long he has studied or why he wants you to listen to him. In that sense it makes no difference where the ideas come from. Their real origin is unknown; we call it the imagination of the human brain, the creative imagination—it is known; it is just one of those "oomphs."

It is surprising that people do not believe that there is imagination in science. It is a very interesting kind of imagination, unlike that of the artist. The great difficulty is in trying to imagine something that you have never seen, that is consistent in every detail with what has already been seen, and that is different from what has been thought of; furthermore, it must be definite and not a vague proposition. That is indeed difficult.

Incidentally, the fact that there are rules at all to be checked is a kind of miracle; that it is possible to find a rule, like the inverse square law of gravitation, is some sort of miracle. It is not understood at all, but it leads to the possibility of prediction—that means it tells you what you would expect to happen in an experiment you have not yet done.

It is interesting, and absolutely essential, that the various rules of science be mutually consistent. Since the observations are all the same observations, one rule cannot give one prediction and another rule another prediction. Thus, science is not a specialist business; it is completely universal. I talked about the atoms in physiology; I talked about the atoms in astronomy, electricity, chemistry. They are universal; they must be mutually consistent. You cannot just start off with a new thing that cannot be made of atoms.

It is interesting that reason works in guessing at the rules, and the rules, at least in physics, become reduced. I gave an example of the beautiful reduction of the rules in chemistry and electricity into one rule, but there are many more examples.

The rules that describe nature seem to be mathematical. This is not a result of the fact that observation is the judge, and it is not a characteristic necessity of science that it be mathematical. It just turns out that you can state mathematical laws, in physics at least, which work to make powerful predictions. Why nature is mathematical is, again, a mystery.

I come now to an important point. The old laws may be wrong. How can an observation be incorrect? If it has been carefully checked, how can it be wrong? Why are physicists always having to change the laws? The answer is, first, that the laws are not the observations and, second, that experiments are always inaccurate. The laws are guessed laws, extrapolations, not something that the observations insist upon. They are just good guesses that have gone through the sieve so far. And it turns out later that the sieve now has smaller holes than the sieves that were used before, and this time the law is caught. So the laws are guessed; they are extrapolations into the unknown. You do not know what is going to happen, so you take a guess.

For example, it was believed—it was discovered—that motion does not affect the weight of a thing—that if you spin a top and weigh it, and then weigh it when it has stopped, it weighs the same. That is the result of an observation. But you cannot weigh something to the infinitesimal number of decimal places, parts in a billion. But we now understand that a spinning top weighs more than a top which is not spinning by a few parts in less than a billion. If the top spins fast enough so that the speed of the edges approaches 186,000 miles a second, the weight increase is appreciable—but not until then. The first experiments were performed with tops that spun at speeds much lower than 186,000 miles a second. It seemed then that the mass of the top spinning and not spinning was exactly the same, and someone made a guess that the mass never changes.

How foolish! What a fool! It is only a guessed law, an extrapolation. Why did he do something so unscientific? There was nothing unscientific about it; it was only uncertain. It would have been unscientific not to guess. It has to be done because the extrapolations are the only things that have any real value. It is only the principle of what you think will happen in a case you have not tried that is worth knowing about. Knowledge is of no real value if all you can tell me is what happened yesterday. It is necessary to tell what will happen tomorrow if you do something—not only necessary, but fun. Only you must be willing to stick your neck out.

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Every scientific law, every scientific principle, every statement of the results of an observation is some kind of a summary which leaves out details, because nothing can be stated precisely. The man simply forgot—he should have stated the law "The mass doesn't change much when the speed isn't too high." The game is to make a specific rule and then see if it will go through the sieve. So the specific guess was that the mass never changes at all. Exciting possibility! It does no harm that it turned out not to be the case. It was only uncertain, and there is no harm in being uncertain. It is better to say something and not be sure than not to say anything at all.

It is necessary and true that all of the things we say in science, all of the conclusions, are uncertain, because they are only conclusions. They are guesses as to what is going to happen, and you cannot know what will happen, because you have not made the most complete experiments.

It is curious that the effect on the mass of a spinning top is so small you may say, "Oh, it doesn't make any difference." But to get a law that is right, or at least one that keeps going through the successive sieves, that goes on for many more observations, requires a tremendous intelligence and imagination and a complete revamping of our philosophy, our understanding of space and time. I am referring to the relativity theory. It turns out that the tiny effects that turn up always require the most revolutionary modifications of ideas.

Scientists, therefore, are used to dealing with doubt and uncertainty. All scientific knowledge is uncertain. This experience with doubt and uncertainty is important. I believe that it is of very great value, and one that extends beyond the sciences. I believe that to solve any problem that has never been solved before, you have to leave the door to the unknown ajar. You have to permit the possibility that you do not have it exactly right. Otherwise, if you have made up your mind already, you might not solve it.

When the scientist tells you he does not know the answer, he is an ignorant man. When he tells you he has a hunch about how it is going to work, he is uncertain about it. When he is pretty sure of how it is going to work, and he tells you, "This is the way it's going to work, I'll bet," he still is in some doubt. And it is of paramount importance, in order to make progress, that we recognize this ignorance and this doubt. Because we have the doubt, we then propose looking in new directions for new ideas. The rate of the development of science is not the rate at which you make observations alone but, much more important, the rate at which you create new things to test.

If we were not able or did not desire to look in any new direction, if we did not have a doubt or recognize ignorance, we would not get any new ideas. There would be nothing worth checking, because we would know what is true. So what we call scientific knowledge today is a body of statements of varying degrees of certainty. Some of them are most unsure; some of them are nearly sure; but none is absolutely certain. Scientists are used to this. We know that it is consistent to be able to live and not know. Some people say, "How can you live without knowing?" I do not know what they mean. I always live without knowing. That is easy. How you get to know is what I want to know.

This freedom to doubt is an important matter in the sciences and, I believe, in other fields. It was born of a struggle. It was a struggle to be permitted to doubt, to be unsure. And I do not want us to forget the importance of the struggle and, by default, to let the thing fall away. I feel a responsibility as a scientist who knows the great value of a satisfactory philosophy of ignorance, and the progress made possible by such a philosophy, progress which is the fruit of freedom of thought. I feel a responsibility to proclaim the value of this freedom and to teach that doubt is not to be feared, but that it is to be welcomed as the possibility of a new potential for human beings. If you know that you are not sure, you have a chance to improve the situation. I want to demand this freedom for future generations.

Doubt is clearly a value in the sciences. Whether it is in other fields is an open question and an uncertain matter. I expect in the next lectures to discuss that very point and to try to demonstrate that it is important to doubt and that doubt is not a fearful thing, but a thing of very great value.