TO THINK, TO DO, TO BELIEVE

Paul Christian Lauterbur

Once again I should like to express my gratitude to everyone here and to greet Your Highnesses and ladies and gentlemen, everyone who is attending this event.

I have been given an unusual challenge by the organizers of the Kyoto Prize ceremonies, one that has also been given to my fellow laureates on this occasion. We are asked to do something that we do not ordinarily do. We find in discussing the matter among ourselves that it is our habit always to give extemporaneous lectures in which we do not read from prepared texts. I will beg your indulgence if I have tried to accept that challenge and do something that is rather out of character and to read at least part of my presentation and supplement it as necessary with extemporaneous remarks.

The talk that I will give here will be divided into basically three parts: a preamble, which no one here has seen; a prologue, which appears somewhere as a summary of the lecture; and the actual text of the lecture which has been prepared. I hope that at the beginning, in this prologue, you will permit me to introduce some personal notes before I present the more formal thoughts that are represented in my formal text.

Some of my earliest childhood memories are of an interest in the natural world, in animals and plants, forests and streams (which also meant hunting and fishing) the earth and the heavens. Those interests broadened to include mathematics, experimentation, evolution and history, and eventually the unseen worlds of forces and atoms. In time, a form of curiosity emerged that has often guided my imagination since. Are some things missing from the world only by accident or for deeper reasons? My vision by the end of childhood was of a sparse, filigree universe in which the network of existence floated in a space of the unrealized and unrealizable. This of course is not the sort of thing that one admits in a lecture in an ordinary scientific conference or in a scientific paper. There one’s motivations are supposed to be much more mundane and immediate and professional. So I almost hope that my words are never noticed by a larger group of my colleagues. But as we think about this question of what exists in the universe, why other things do not exist, we can pose problems in a more specific way.

Why do mountains not move, or puddles and grains of sand evolve and live? Complex molecular structures based on silicon do not seem to share the propensity toward life of those based on carbon. Is this difference necessary, or accidental?

A very naive question of this kind was an early motivation for my interest in experimental science, because I began to wonder. From what little I knew of chemistry, had learned by reading here and there, there seemed to be a great similarity between the fundamental chemical natures of the elements carbon and silicon, but at the same time the consequences of that chemical nature seemed to be quite divergent. So my thoughts and some experiments in my home basement laboratory turned toward making molecules containing both carbon and silicon, so as to explore a hybrid organic-inorganic world. I scoured the libraries in my small town and the nearest city to learn what was already known. Incidentally, that was not always as easy as it sounds. If one has interests that seem to go beyond the ordinary subject in the classroom at one's age, I found that the natural response of a librarian was, "Oh, don't you wish to see a book on chemistry for children?" I would say, "No, I want the volume of the Journal of the American Chemical Society from 1939," and it was easy to throw librarians into confusion. I occasionally required adult intervention to be permitted to access to that part of the world of knowledge.

But to go back to my personal experiments, many strange results and invaluable experience with laboratory work, but no real discoveries, came from this work, although I still do not understand the results of some of those experiments of almost 50 years ago. And I suspect if I were to repeat them today with 50 years more knowledge, that I would not understand them still. Because any of you who have been involved with experimental science know that experiments that you can readily understand and interpret are a minority, that one is fortunate to be able to design and to carry out and to interpret. Much of the work of science, like much of the work of filmmaking, for example, goes on behind the scenes and is never seen by those who look at the final product and admire its form and shape and ingenuity, but never know all of the false starts and the horrible errors and the confusions that went into the creation of that final product.

After college, I went to work in a research institute with only a bachelor's degree, without any graduate degree. The reason for that was that I had grown very tired of sitting in classes and listening to professors. I wanted more of an opportunity to work with my own hands, to do experiments, to have a more direct relationship to scientific investigation. As I said, I was tired of listening to professors at that time, and I could not imagine and would have been horrified to know that one day I would become a professor myself. I worked in a research institute with a group that made and studied organo-silicon compounds. I was very fortunate that I was able to find a job that could continue the interests that I had had since childhood. At the same time, by the way, the same position allowed me to continue graduate work toward a Ph. D. in chemistry in my spare time, nights and so on, when I was not working at my full-time job. But while I was working in the laboratory in the research institute, helping to synthesize organo-silicon compounds, helping to test polymers made from those compounds, to try to understand the individual molecular properties and the collective properties as expressed in industrially important materials—insulators, polymers, rubbers—I became interested in the very new technique of nuclear magnetic resonance, or NMR. That had been discovered about 1946 and a few years later the possibilities of using it for the study of structures of chemical molecules had become apparent, and I became interested in using it to study the motions of molecules and the silicon containing rubber, and my old interest, the differences in electronic structures between carbon and silicon compounds. Nuclear magnetic resonance fascinated me because of the clarity with which it apparently could reveal molecular structures and behaviors. And since I never cared to do things in a more complicated way than necessary, a method that presented the data in ways that seemed closely linked with a shortest possible chain of reasoning to certain features of molecular structure was extremely attractive.

As the years went by I worked in that field, and that clarity helped me to reveal some of the fascinating aspects of the natures of both organic and inorganic molecules and certain of their chemical reactions. During this time my interests were, as I said, in chemistry, and gradually drifted away from being focused on the chemistry of silicon to becoming more focused on the chemistry of ordinary organic compounds. In the late 1960s it became apparent that NMR techniques were becoming powerful and versatile enough to attack problems involving biological macromolecules, such as enzymes, nucleic acids, other proteins, and I began to turn my attention back to that aspect of the world of living things. I did some experiments with enzymes, doing nuclear magnetic resonance studies, trying to elucidate the ways in which their structures changed when they bound molecules in order to catalyze chemical changes in biological systems, but before I had gone very far in that direction, circumstances arose that ignited in my mind the idea that NMR could be used to make detailed images of the interiors of complex objects.

I want to describe a little bit of the background there so that it will help to dispel the myth that science develops by deliberate, planned, logical processes. My opportunity to have this idea arose because I was on the board of directors of a small instrument company. The founder of that company, as often happens when small companies grow, had found that managing it had gone beyond the point at which his skills were sufficient, and the company had run into a great deal of financial and technical difficulty. In May of 1971, as the summer began and I was able to get away from my university duties, I was asked to take over the direction of the small company. The alternative was instantaneous bankruptcy if no one was found to attempt the impossible, to rescue the company from its problems. I attempted to do so, and there are many stories that we have no time for here today about my adventures in trying to learn, under extreme pressure, how to manage a company that was almost ready to disappear forever unless some miracle occurred. A miracle later occurred but it was not my doing. But while I was there the company laboratories were being used by other research groups to measure NMR properties of tissue samples taken from rats that had malignant tumors, taken from those tumors and from other organs and tissues in the animal, and it was observed and confirmed while I was actually watching the experiments that there were measurable differences in the NMR properties of the tissue specimens that were removed from the animals after they were sacrificed, placed in very small glass tubes and put in the NMR machine. I was only a chemist, and it seemed to me that making measurements on tissues from animal and human bodies by surgically removing them was a process that could be improved on, I hoped. There must be a better way of measuring those properties of the tissues, which seemed to be quite useful potentially, without cutting open the animal or human in order to do it. And so I asked myself that same evening whether there might possibly be some way to identify within an intact complex object the sources of the NMR signals that emanated from it.

I will not attempt to give a short course in nuclear magnetic resonance imaging techniques to this audience. I will just say very briefly that the idea that revealed itself to me was one that had in a sense been too simple for anyone else to think of. So perhaps my predilection for very simple approaches to problems was what enabled me to grasp the possibilities. I will get a little bit technical for just a moment. Those of you who are interested will feel as if I have abandoned them if I do not speak a few words here on the technical side. The idea was to make use of the fact that the nuclear magnetic resonance frequency for the nuclei, for example, of hydrogen in the water molecules of the body, was directly proportional to the strength of the magnetic field. If the magnetic field was made to vary from one region to another, my left ear to my right, the frequency of the nuclear magnetic resonance signal from the one location would be different from the other. And so one would have a number of frequencies coming from an object. If, instead of putting it in a very uniform magnetic field as everyone had been doing for most experiments for many years, if one placed it in a magnetic field in which the difference from one place to another was known and controlled, then the numbers that represented position, millimeters, would be converted into numbers representing frequency, hertz, cycles per second, in the radio frequency region of the spectrum. So essentially the problem was converted from one of making images to one of measuring spectra, and hence it required a very different point of view, a very different methodology than all of the other methods of imaging that had ever been used. Microscopy with light, microscopy with electrons, astronomical imaging, cameras, your own eyes all work on a different principle. This was a new principle and therefore it was originally difficult to grasp.

Because it was a new principle, I decided to give it a name, and searching around in Greek—I knew nothing of Greek but I could find the Greek roots of various English words—I found a word that for reasons I will not attempt to explain to you looked as if it might represent some version of the idea that I had, called zeugmatography. I heard it spoken in the earlier descriptions of my work so I thought I would bring it out. It has since dropped from use. I used to speak of “nuclear magnetic resonance zeugmatographic imaging,” which is quite a mouthful. As you can imagine, at least as happens in the United States sometimes, if you give a name to your child that has a very difficult or non-euphonious aspect to it, the child may attempt to use other parts of the same name and suppress the difficult part. So what has happened is it has become “nuclear magnetic resonance imaging” and then for brevity “magnetic resonance imaging” and then for even more brevity, “MRI.”

Following that date in 1971 when I realized that there was another way to make pictures, most of my scientific activities have veered off in new directions away from molecular science. Imaging science and technology, especially as applied to medicine, occupied much of my time. The basic idea and simple experiments initially were regarded by many others as trivial, unpatentable and even unpublishable. It turned out to be a cornucopia, spilling out more ideas almost as rapidly as they could be written down, and much more rapidly than they could be tried in my laboratory or any other laboratories around the world where other people were doing similar work. Within ten years, as you heard, magnetic resonance imaging was brought to the point where it could be used clinically. I had expected it to happen much more rapidly. The slowness was partly because it was necessary to build magnets capable of giving magnetic fields adequate for this purpose on a much larger scale than had ever been done before. Most nuclear magnetic resonance work had been done with objects a few millimeters, a centimeter or two in size, and so the basic equipment, the magnet had to be dramatically scaled up. That took time. Also many of the other techniques required significant modification. This was done in academic laboratories, eventually in industrial laboratories, and finally devices began to be produced that could give imaging that would be adequate for commercial use and for use in medical clinics. The field has continued to develop and to reach into new areas in medicine, biology, materials science, chemistry, and now even into studies of the human mind. That again will be touched upon in my workshop lecture tomorrow.

But we have wandered very far from my original interest, haven't we? But why don't the mountains move? We now know that they do, of course, but at the mercy of blind tectonic forces, not voluntarily. Or are we being too anthropomorphic? We do not yet understand human or animal will and consciousness. Could the great continents and their underlying structures that move around the earth, or the earth itself share our illusion of free will, making their long slow plans while we skitter about like a cloud of gnats? Perhaps cognitive science, chemistry and geology will one day allow us to pose such a question as a truly scientific one, and to distinguish more clearly among the many forms of existence and non-existence.

In a way, thoughts can come full circle, because my work in attempting to understand how we might learn more about the human mind brings us back to the question of what is a mind, what is will, what is consciousness? Are they incorporated uniquely in the human brain? Or as many people have asked, can they be incorporated in artificial structures like computers? Or if one wants to wander more toward the realm of science fiction, could they be incorporated in other natural structures as well? It is exciting when science even hints at the possibility that loose speculation and poetic concepts might someday be formulated in such a way that they could be subject to careful, responsible, reasonable experimental test. Perhaps we are getting close to that time. But in order to keep our balance among such new possibilities and wild thoughts, people must, as the Buddha taught in "The Way of Purification";"Train their minds and keep them broad as the earth, unlimited as the sky, deep as a big river, and soft as well-tanned leather."

And now I come to the notes that were remarked upon earlier, based upon a quotation from Hans Neurath: "Science is like a boat, which we rebuild plank by plank while staying afloat in it. The philosopher and the scientist are in the same boat."

Is life any different, in all its varieties of impulse and understanding? Morals, arts and politics, ethics and social systems, religions and economic systems, share the same plight. The planks of the boat are always rotting in warm, quiet waters or failing catastrophically in storms. Failure to keep up with the rebuilding will stunt human lives, bring companies, nations, cultures and civilizations to ruin, and leave sciences and philosophies dull and irrelevant. The problem is to save hard-won understanding despite the constant changes. Mathematical theorems and *haiku* enrich our humanity over millennia, and questions that were posed long before they were ever written down still perplex and challenge us.

It is often noted that the rate of scientific and technical development accelerates. Each new technique and level of understanding enriches others, and the rich network expands in scale and complexity at a headlong pace, maintained by links across time and space. Less noted is a parallel growth of human culture in a broader sense because its growth seems to be dominated by the completion of successive themes and impulses and by confusions during the growth and consolidations of new ones. More and more of these mature cultural complexes are preserved into later eras to influence later works and those with different roots. All is not lost to short human memories and the vagaries of history as a human network reaches farther around the world and backward into time. Architecture and art have long had opportunities to survive, then literature and music, and now we enrich our lives with performances from the past, as in the cinema. Something is always lost; no human mind can hold the riches of all ages. Wisdom and knowledge and experience, of thoughts and acts and beliefs from the infancy and childhood of all humanity, are increasingly woven into our contemporary souls. The future grows from them, and the seaworthiness of our boat depends on our keeping them in balance and integrated as we build and rebuild each day, each year, each generation.

The constant theme, one that a scientist has to face every day of his or her life, and that all of us have to remember when we are forcibly reminded quite often, is that we do not know the future. I spoke a few minutes ago of the enrichment of human life from the past that we more and more hold within our grasp, so that we can face the future with memories and insights, with more knowledge of alternatives and possibilities than we have ever had before. But we still do not know it, we can only be better equipped to face it.

The obvious statement that we do not know the future, however, changes its meaning over the generations. Once the meaning was relatively simple, although it certainly did not seem that way to the people involved. There would be births and deaths; expected but at unknown times. Enough food would be available to last through a long cold winter or drought, or it would not. Epidemics, snakes, tigers would strike, there would be raids and wars and famines. As time went on, human societies evolved, longer cycles of gain and loss were observed, tales repeated became myths and then faded. New tales were repeated, new myths formed, faded and were lost. With written records came a sense of historical change, as progress and sometimes regarded as the loss of a golden age, with these changes, these broader, deeper, longer changes moving behind the ephemeral cycles and accidents and bearing them along.

Now we feel those background forces rushing to the fore, competing for our attention with the old incidentals of individual lives and national victory and defeat. We are coming to expect systemic change to sweep us along during the decades of our lives. Our parents' advice survives for us sometimes only as attitudes and generalities. We fear that our children may receive from us not even that much. It is easy to deny that such changes are deep, essential and lasting; much does not change, and the winds blow one way and then another. But under such denials is often fear. One writer has even described the compounded acceleration of change as a rush toward a mathematical singularity, where the rate of change approaches infinity and the future becomes not only unknowable but beyond our understanding.

Perhaps. Or perhaps that is more like a death wish, a cry of despair, when we must climb but there is no resting place in sight, and the slope grows every steeper and the landscape ever stranger. So long as the slope is ultimately a collective change in human society, will individual confusions and limits, and the fragilities and rigidities of human societies, ultimately divert the energies driving scientific and technological change into other channels? If we cannot cope, will we look elsewhere for what will bring some kind of progress to our lives and those of our societies? This question is itself a part of the problems. It implies a breakdown of our limited faith in even our weak predictive abilities and the principles upon which they are based, thus the question certifies its own significance. Is this an invitation to a new form and depth of despair? No. The unknowable future is naturally confronting us again, in a new form. Once, the personification of natural forces and objects and events gave humanity an illusion of understanding and control. Beyond the small-scale patterns, the random events, cyclical patterns, progress, and the compounded acceleration of progress, looms the next unknown, its shape vague and menacing, even more so because its very existence is debated.

I think we can see in some of the social and political stresses that are breaking out in our own societies from time to time examples of the difficulties that we all face in understanding, appreciating, having some confidence in the ability to see forward at least a little bit into the future. I might even say that an example of that is the recent elections in the United States.

What can be done? What has always been done. Prepare. Think, to be prepared to understand change; act to control what can be controlled; believe, in values and principles that are the outriggers and rudders that guide the vessel of humanity through the waves of confusion toward always unknown destinations.

On the way to Japan on this trip I was once again reminded of and impressed by the exploits of the Polynesians in exploring the expanse of the Pacific Ocean, an expanse greater than the land mass on earth, in vessels that were in a sense primitive and in another sense highly sophisticated, making use of all of the intrinsic capabilities of human beings to spread their civilization across a vast and almost entirely empty part of the earth. That should be an example to the rest of us who, being relatively bound to the land and to what we can see, not having to think too often about what may be beyond the horizon—or even worse, not be beyond the horizon—to remind us that humans have been able to surmount such conditions before. And as we think and do and believe, we should do those with the virtues of lightness and balance and humor that keep desperation and confusion from sliding into the personal and collective fanaticisms that destroy what they would save. Whatever other meanings we may discover or invent, the purpose of life is life, the life whose evolutionary imperatives sing in the blood, shaping the goals and tactics of survival.

If there is a singularity in our future, it may take many forms, or more likely several at once. Time has been jokingly described as that which keeps everything from happening at once; in that sense we feel the approach of the end of time, with the sense of doom that periodically suffuses some religions. This sense of doom is quite distinct from the flash of nuclear weapons, uncontrollable pandemics of new diseases, environmental collapse, a collision with a comet, or even the retreat from reason and order that is the stuff of stories and books. This is the doom of success, achieving our goals and dreams. Individuals and societies are often defined by their troubles, and we may lose our coherence and balance with peace and prosperity, when we understand our brains and bodies so well that we cannot hold back from tampering with them much more effectively than we do now.

Let me stop for a moment. That understanding brings us back again to the revolution in the understanding of the physical bases for life, for the mind, that the techniques of magnetic resonance are in their own small way contributing to. If I have any credentials for trying to think about these matters or to speak about them, it is because the responsibility that I feel when I try to work with my colleagues in this field, to understand what we are doing, to choose right paths of work, has led me to think, as deeply perhaps as a chemist can, about what it means to understand the mind. You should realize that I have no professional credentials for speaking of these matters. On the other hand when I look back over my life, I've actually never had any professional credentials for doing anything significant that I have ever done. So at least that gives me a sense of perhaps unwarranted bravery and allows me to speak of these matters.

With that aside, one finds a great deal of belief in the contemporary literature of the science of the brain and mind that we are now able to pose the questions of what is consciousness?, what is will?, in ways that allow scientists to address them in terms that have not hitherto been possible for philosophers and for those providing religious enlightenment. It is an aspect of science that the world is always stranger than we imagine. There are those who have also said that it is possibly stranger than we can imagine. That is another feature of the future that looms before us. But it is certainly stranger than we can imagine, and any working scientist constantly encounters the reality that what you observe, learn by experiment, introduces new concepts, new ideas that no amount of sitting around and thinking could ever have produced. We are only a part of the universe. The universe is much greater than we are, much greater than we know, and we have to live with it humbly, respect it and learn from it. And as we learn more about how to ask questions that can be experimentally tested, that can be the subject of scientific investigation rather than of contesting schools of theology and philosophy, which have their great value but are only one part of our way of understanding the universe, as we learn how to investigate scientifically these questions, we will learn more about what it means to think, to be human, what our relationships to the animal world are, to what degree our evolutionary predecessors and those who have evolved in parallel with us to the present time share our innermost experiences. And as we learn how the mind works as a function of the brain, there will be confusion, as there has always been through the development of science at every stage, about whether this new knowledge is taking from us some of the poetry that allowed us to live in peace and tranquility and with beliefs that gave us confidence in our understanding of the world.

We are approaching a frontier when our understanding of ourselves will cast doubt upon our understanding of ourselves. When this happens, how many individuals, how many parents, how many societies and cultures will be satisfied to have those they love and care for and are responsible for be less than it seems that humanity can be? Not some deviant, wild Frankenstein impulse, but the impulses of decency, of love and caring will eventually lead us to make use of this knowledge. That will be a great test of humanity’s wisdom, and it will be a great test of how much we have learned throughout all of the millennia of our civilizations, how much we have learned, how much we have remembered, how much we are able to integrate this knowledge, how much we are able to suppress the discord that arises among individuals and societies when they extract from this heritage different views of right behavior and of how the future should look.

All humanity will be engaged simultaneously in this effort. In the past many societies have grown in relative isolation for centuries, sometimes for millennia, working out these questions among themselves. We all know that is no longer possible, and we are in the process of forging a complete humanity for the entire world and at the same time understanding anew, redefining what we mean by humanity, what we mean by the functions of love and respect and conflict among humans on this earth. You will find in literature, not just in the genre literature of science fiction but more broadly as well, a concern that all of human civilization up until now is essentially all of human civilization, that we have done it, that our time is coming to an end; that as we learn to imagine that thought, perhaps emotions, individuality, will and consciousness may not be defined solely by the configurations of the neurons in our brains and we may even learn how to endow our creatures with them, that we may pass to the point where we can say proudly: This was humanity, let us see what comes next.

The thought is often expressed that we may create computers and those computers may create other computers that can keep us as pets, the way we keep other animals. Or that we may seed an autonomous nanotechnology that can develop, evolve more rapidly and supersede not only humanity but the entire biosphere. Will these thoughts, these fears, these concerns, these visions be the challenges that will carry us to new heights or successes? Or will these successes and heights bring us to some kind of a degenerate nirvana and eventual extinction in our present form?

These are some of the nightmares of scientific success, that the pace of change will leave ordinary humans, or all humans, lost and uncomprehending. And we must all ask ourselves, is it better to sail boldly into such unimaginable futures, or to give in to a common human impulse to tear down and destroy, to retreat to earlier stages in our human development and in our societies, is that the way to go? Certainly the utopias that are written about often involve the wish to return to an earlier simple time, when people were not puzzled or perplexed, when somehow hostility and anger and arrogance had all disappeared and we could live peacefully with one another. In the Judeo-Christian tradition it is the Garden of Eden that could come again; it is different in other cultures and traditions. But I think we know from contemporary history that any attempt to turn back the clock involves unacceptable violence to individual humans, to society, and the destruction of any rational and humane future. Certainly we can never forget what we know now. We know where we have come from, we know where we are, we don’t know where we are going, but we cannot forget this present stage in the development of humanity, we cannot forget our aspirations, our hopes, our dreams. If there is some better way than bloody regression or bold sailing into the future, I do not know what it is. Perhaps someone will find a better way. Perhaps that is a challenge that we are facing. As I said earlier, perhaps the energies of mankind can find a benign and hopeful diversion into other channels that will find continual fulfillment.

The boat sails on, growing and changing and leaking and creaking ominously as it goes, across uncharted seas. It has been sailing for thousands, tens of thousands, hundreds of thousands, millions of years. Can you imagine the consternation in the minds of humans when fire became common? When new weapons, stone tools became common? When agriculture came into human life and destroyed the fabric of society as it was then known? Mankind has passed through many such revolutions, and they have never known as they faced these problems, when the glaciers moved down across Europe, when the rivers dried up, when many events occurred that were unimaginable, our ancestors have never known the future course. They often guessed and imagined. Their guesses and imaginings became myths, religions, traditions, taboos. Will ours be any better? Well, it has never been easy to be human and I doubt that it ever will be. Will our boat disappear into the depths, reach a happy shore, or undergo a metamorphosis into something entirely different? We have never known, and we do not know if we ever will know. Still, every day brings new opportunities for thought and action and belief, new opportunities to engage ourselves in being fully human in whatever sense that is defined by our collective autocatalytic evolution.

Thank you.