

The Practical and Sentimental Fruits of Science

Frank Oppenheimer, Exploratorium

Fifteenth Anniversary Awards Dinner Speech, November 1984

In December of 1984, the Exploratorium held its Eighth Annual Awards Dinner. The year also marked the museum's fifteenth anniversary. At the dinner, Frank spoke on "The Practical and Sentimental Fruits of Science." The complete text of his speech is reprinted here.

Thank you all very much for coming. I also want to thank the staff of the Exploratorium. Because of our roof reconstruction this place was open to the rainy atmosphere over the weekend when seven thousand people came. Then, to compound the mess, it rained all day yesterday. Yet the entire staff conspired and worked to make this place look as nice as it does tonight.

I was extraordinarily honored when Bill Hewlett let us honor him at this dinner. It is for us a great privilege to be able to do so.

I'm not going to talk about the Exploratorium. I resist the temptation to do so because I want to talk more broadly about science. There are some aspects of science that I think are not generally understood. In the first place, when people talk about civic cultural institutions they do not usually include science museums as part of their image of culture. Before we started this place, I noticed that universities would have museums of art, geology and anthropology exhibits, but rarely museums of the physical or biological or social sciences. Yet when we describe older cultures, we always include their world view. When we think of the Druids we are impressed by how well they had recorded the seasons and how well even earlier people had recorded eclipses and tides. We show their tools and their technology; we talk about all their myths about nature and include all these as a part of what we think of as culture in distant civilizations.



Awards Dinner

But these are also part of the culture in our civilization. One of the reasons that physics, chemistry, and biology are not assimilated into our view of our culture is that these subjects are taught primarily as vocational ones. Furthermore, they are taught unimaginatively and are not integrated with other aspects of our culture. I hope this situation can change. It would be good to come back to the days in which physics was thought of as natural philosophy.

The basic objective of science is to discover, understand, and unify what's happening around us, whether in living things or inanimate things. Very often people talk about the scientific method, but I believe that the way of understanding in science has a great deal in common with the way of understanding anything. Yet there are a couple of very special things about science that are not part of its methodology really, but which are crucial to its progress. One of these is that if you are genuinely trying to understand what's going on around you, then there's no point fooling yourself, or, for that matter, fooling any of your colleagues. Within the scientific community there is a tradition that anybody who fabricates data is completely ostracized. This tradition is one of the basic tenets of science, and science

has traditionally been one of the very special strongholds of that tenet. I wish it also applied to politicians and advertisers, so that they would ostracize people who willingly and deliberately fabricate data.

One of the nice things that is true of the Exploratorium is that people trust it. We don't "rig" any of the exhibits; the exhibits do not show things artificially. The natural phenomena are there, and the visitors can ask questions of the exhibits. The exhibits can then answer these questions because they behave according to nature.

There's another very special property that is true of the pursuit of science and essential to its ability to flourish. It has to do with the fact that the effort and activity of trying to understand something can be, and often must be, separated from, divorced from, the process of trying to accomplish something, and from the business of doing, of making a living, of constructing. A great deal *is* learned in the process of doing, but one can rarely stop the doing in order to look into some unexpected behavior more closely or to follow the side-dreams of one's curiosity far enough to complete the understanding. I know that during World War II, when we were working on the separation of the readily fissionable isotope of uranium from the more abundant one, we were in a hurry. We couldn't stop to look at all the new things that we saw. We had to start with a gas discharge, like a neon sign, but through the gas of some uranium compound. These discharges produced separated beams of the two isotopes. These beams started as extraordinarily small currents, just tenths of microamperes, but eventually ended up in factories that produced hundreds of amperes of uranium ions. We ran into trouble. When we tried to increase the current, we got violent random fluctuations in what was happening - "hash" we called it. But we couldn't stop to examine the nature of discharge plasmas; we just had to try something different. If our change made the current larger, we did more of the change; if it made things worse, we did less of it. There was no way of getting the job done and at the same time trying to

understand the phenomenon. I had the same kind of experience when, during the 1950's, our family was farming. We planted a certain wonderful grass: Amur wheat grass that was selling at a dollar fifteen a pound for the seed. We decided to grow the seed as a cash crop. We plowed up eight acres of virgin soil and got a wonderful harvest that filled our granary with sacks of the precious seed. *But not one seed was fertile*. However, we couldn't stop growing the grass to understand why. Besides, by the next year there was no point in understanding it since the price of the seed had dropped from a dollar fifteen to thirty cents a pound. And so we just continued to have a good hay crop, but without ever having a seed crop.

Bringing up children provides another example of the impossibility of combining research and activity. For example, I have always wondered whether major and minor keys had something special about them, the minor one being intrinsically sad. So after my daughter was born, when I was happy or we were dancing, I would sing or play music in a minor key, and when we were sad, I'd play music in the major scale. But it wasn't a very good experiment because there were too many outside influences: other people sang songs which sort of destroyed my experiment. Whether you are bringing up children or teaching or farming or developing products, it's very hard to really look into things at the same time. The very special thing about science is that one isolates the business about finding out about something from the business of doing it. Of course, many very fundamental properties of nature have been discovered in the course of trying to get something done, but the establishment of separate research environments in which people are paid just to find things out has been a key element that has made science flourish.

The experiments with cosmic rays that Dr. Panofsky mentioned when he introduced me provide an interesting example of the way in which the course of fundamental research can fruitfully be redirected in midstream. In 1947 the Chairman of the University of Minnesota Physics Department, Jay Buchta, had brought



We believe that this is Frank Oppenheimer (on the left) adjusting a balloon-borne cosmic ray experiment

together a group of physicists to study cosmic rays at very high altitude. The General Mills Corporation was developing huge balloons that could carry an eighty-pound payload to an altitude of one hundred thousand feet (about twenty miles). These balloons made it possible to adapt standard instruments to the study of nuclear reactions using very-high-energy cosmic rays well before the high-energy accelerators of today had been developed. We accordingly built a cloud chamber that enabled us to successfully photograph nuclear interactions. But the most surprising results came from a stack of photographic plates that we had added to the payload. These plates did not show incoming cosmic ray hydrogen nuclei (protons) very well, but they did show, when developed, heavy dark lines that were the tracks of fast moving, highly electrified particles. We had made a discovery! These tracks were due to the presence, in the incoming cosmic rays, of the nuclei of all the elements: carbon, oxygen, iron, etc. Up to that time, only the nuclei of hydrogen had been observed in incoming cosmic rays.

This discovery immediately turned around the direction of our research. We began to study the origin of cosmic rays and what happens to them as they move in our galaxy. Our thrust became more involved with aspects of cosmology than with the study of nuclear physics.

Another manifestation of the central role of separating research from problem-solving is illustrated by a controversy that raged during the nineteenth century concerning the age of the Earth. From purely geological evidence, sedimentation rates, etc., geologists concluded that the Earth must be well over one billion years old. But this age contradicted evidence provided by the high temperature of the interior of the Earth, hot springs, molten lava, etc. The Earth radiates this heat to cold outer space much faster than the sun keeps the planet warm, so that the Earth would cool fairly rapidly, in about one one-hundredth the time claimed to be the age of the Earth by geological evidence. The solution to this problem could not have come from either the geologists or the physicists of the time. The solution came from a completely different kind of research at the beginning of the twentieth century: the study of radioactivity. There is enough uranium and thorium in the Earth's rocks to keep the Earth warm.

This pattern of discovery—the bringing together of two initially completely independent domains of basic research—is characteristic of progress in both the practical and the sentimental fruits of science. It is clearly shown in the invention of lasers, semiconductors, and super conductors, and in the many roles that nuclear energy can play both on Earth and in the stars.

In general, what science has done through its wandering explorations is to discover things that were happening in nature that nobody knew were happening. These newly discovered phenomena—whether they have to do with semiconductors, radioactivity, induced emission, or electromagnetic waves-have provided the raw materials for new invention. Virtually every newly discovered natural behavior has opened up a plethora of new inventions. On the other hand, without this continuing insertion of fresh raw material, we become stuck. We then go 'round and 'round in the same path, both technically and philosophically. It was largely this lack of "raw material" that caused invention to be mired down before the scientific revolution, before

people had the privilege and were even paid to go off into a corner and look into nature apart from actually getting something done.

So our support of basic, almost playful research has to continue. Too often it is not understood how this special, or, if you want to call it so, this ivory tower nature of science is crucial to any sort of progress.

There are industrial labs that have this academic quality. The Bell Lab has had such a reputation, and many other industries have followed suit. But for the most part, industries can only afford to do research to get a limited domain of particular things done; they can't wander all over the map because they have noticed something that aroused their curiosity.

There is another aspect of science that has caused much confusion, especially among the lay people and even, I think, among the scientists themselves, especially the social scientists. Scientists are now very often asked to predict what's going to happen. But I see no reason why they should be particularly good at doing so. The confusion comes from the parlance of science. We say that a crucial test experiment for a theory comes about because the theory "predicts" something, and then you find it. But what these theories predict is not the future: they do not tell what's going to happen. When Einstein predicted that light bends as it goes by the sun, he didn't predict something that was going to happen in the future. It was something that was happening all the time—that always had happened and always will happen.

Most crucial experiments, most predictions of theory, are not predictions of what's *going* to happen; they are predictions that if you look at the right time, in the right way, and with the right instruments, you will find what is happening. In this sense the theory helps you discover new things that are going on in nature. But the word prediction has led people to think that one's understanding of nature is going to let us know what actually will happen in the future. Science can tell what is happening, what has happened, often what



Arno Penzias and Robert Wilson discovered the 3K background radiation - the echo of the Big Bang - doing satellite research for Bell Labs while using their unusual radar antenna .

can happen, and sometimes even what cannot happen because of the conservation of energy or some other very broad principle, but it hardly ever can tell, purely from understanding, what *will* happen.

Yet a by-product of science *has* contributed to our ability to predict and therefore, indirectly, to our sense of security (people have always wanted oracles). In fact, most predictions are based on pattern recognition rather than on understanding. People could predict the tides long before they knew anything about gravity. Prediction is based primarily on observing patterns often enough that one can assume those patterns will repeat again and again. Such repeatability is the basis of our predictions, whether connected with childrearing, the mode of operation in committing a crime, the course of a disease, or the changes in business cycles.

How does one observe patterns? One has to use one's senses, and it is science that has provided the raw material of natural phenomena that has enabled us to invent ways of extending the range and sensitivity of our senses. This extension of our senses involves our ability to see through things: it has to do with weather satellites, with the perfection of microscopes, telescopes, and infrared binoculars. All kinds of ways of seeing,



Over a period of over 1400 years, observers 4000 years ago, noted the patterns of motion of the sun and moon. Stonehenge was built (in many stages) as an astronomical calculator to predict celestial events.

hearing, sensing motion or detecting molecules have been invented. These have vastly expanded the acuity of our senses, our ability to observe patterns, and therefore our ability to feel a little more secure because we think we know what's going to happen.

The people who can do this observing are not necessarily using science to observe patterns. We are all reasonably good pattern recognizers and some of us are uncannily good. Doctors must be very good pattern recognizers; artists are pattern recognizers; the people who watch radar and observe what's happening with airplanes don't have to know any science to discern the patterns of approaching airplanes. So I think scientists on the whole should be a little more humble. They should understand that it isn't their scientific training or knowledge that enables them to predict what's going to happen. If the scientists say that such and such a thing *can* happen, they may well be right. However, they rarely have any compelling scientific justification for saying that something *will* happen. I don't think they have any special right to say that. But if they *do* say it *can* happen, whether it's a nuclear winter or destruction of the ozone layer, then the public, although it cannot be sure it's going to happen, should nevertheless be alert to this possibility and be prepared to react quickly to prevent it from happening, especially if it is catastrophically irreversible, as is the case with nuclear winter. It is in this sense, I think, science and understanding can provide a real service, but I am really worried by the fact that many scientists too often

believe that they can tell us what *will* happen.

The discoveries of science have clearly done more than extend the senses and thereby improve our ability to discern patterns. These discoveries have also enabled us to invent tools that enable us to do what we want to do, whether through the use of computers, lasers, electric motors, or airplanes. Furthermore and very importantly, science has enabled us to construct protective environments that shield us from the ravages of nature. We don't really control nature, but we do have air conditioners, ocean liners and space suits that—rather than change the climate, the ocean or outer space—frequently enable us to live in a protective mini-environment where we do have control. These practical fruits of science—the extension of the senses, the tools, and the mini-environments have really made a huge difference in the way live now compared to the way they lived two hundred years ago.

But science has done a lot more than that. It has changed the way we feel about ourselves, and our broad notions of how we fit into nature. Our understanding of the history of the expansion of the universe and the formation of galaxies and stars meshes with our understanding of the evolution of living organisms and of the Earth. All of these form an interconnecting view of change and development. Furthermore, our detailed knowledge of the workings of nature has changed what we fear and the way in which we fear. We no longer think of lightning strokes, earthquakes, or floods as punishments inflicted by angry gods. Such events only rarely have any connection with human behavior. We understand enough about nature that we know how to react to and in some cases protect ourselves from lightning and floods. We certainly do not have to rack our souls trying to determine what we did wrong and why we are being punished. In general, our understanding enables us to simplify our actions and choices because we know in advance which of all the possible reactions we can take are relevant. This simplification of response, this ability to substitute specific fears for vague terrors, can bring to us a sense of peace and order.

Certainly this process is manifest as a sentimental fruit of science in the way we now react to the inanimate world.

But unfortunately we are still filled with vague fears. It often seems to me that the total amount of human fear may be constant. For although we are not as filled with haunting fear of earthquakes, bacteria, or lightning, many people are increasingly scared of what people can do to each other, whether by using guns and clubs in the streets, or with nuclear bombs or carcinogenic food and environmental pollution. Too often our collective responses to the fears of what people can do to each other are irrational, mutually incompatible and confused. For the most part, people are barely able to distinguish which of all the possibilities for inflicting human terror are most threatening.



Perhaps social scientists can use what they discover about the behavior of people and societies to provide the raw material for inventing institutions that protect people from people and which, at the same time, provide social tools that enable people to satisfy their innate physical, mental, and emotional needs.

Whether they can do so is not yet clear. Certainly, social scientists have developed many new tools, social indicators that, so to speak, extend the range of our collective social acuity for observing patterns. Improved pattern recognition enhances our ability to foretell the future. But this ability is not very well developed even in the much simpler domain of the physical sciences.

Unfortunately, many social scientists have concentrated on using their ability to predict the future as a test of their understanding and the reliability of their instruments. But they too rarely use observations and measurements primarily in order to get a better understanding of what is actually happening in people and in societies. There is one outstanding example of social invention that may have been the result of such deeper social understanding. During the seventeenth and eighteenth centuries, French philosophers developed the notion that it is impossible to govern a populace without having at least the implicit consent of the governed. This insight led to the recognition that such underlying consent could and should be expressed as overt consent, and thereby led to the constitutional inventions that rely on popular suffrage.

On the other hand, I find that the general use of the Stanford-Binet IQ test provides a counter- example to my admittedly somewhat speculative example of constitutional invention. Almost immediately after its development, the test was used to help judge how well students would do in college, etc. Certainly measurement is an important and usually essential step in the development of the sciences, but the ability to predict what is *going* to happen is a poor indication of the quality of the fundamental sciences. The IQ tests have not really illuminated the nature of intelligence any more than Galileo's invention of the thermometer in the sixteenth century gave insight as to the nature of temperature. This insight was not arrived at until late in the nineteenth century. And temperature is a much simpler concept than intelligence.

It is such considerations that lead me to believe that the pursuit of the fundamental social sciences can eventually provide the raw material for social inventions that will significantly reduce our currently paralyzing fears of what people can do to other people by “pushing the button,” by local and world-wide lawlessness, or by the coercive nature of police and militarily dominated governments.

There are many important sentimental fruits of science, two of which I would like to touch on before closing: the unity of nature and the meaning of heresy.

One of the most elegant and satisfying achievements of science is the discovery of widespread unity in nature. For example, every atom of carbon in each galaxy, in each star, has the same properties and emits exactly the same color of light as does our earthly carbon. The diverse phenomena of nature do not require the assumption of diverse forces or causes. Electricity and magnetism are coupled, and together they explain the existence of radio waves, light, and X-rays. The aurora borealis is not very different in origin from the light given off by a TV screen. Lightning is equivalent to the shock to your fingertip when you touch a doorknob after shuffling across a rug on a dry winter day.

The list of phenomena that can be explained by virtue of electromagnetic forces is almost endless. But there are still many gaps. Gravity and electromagnetism continue to defy unification despite the many attempts by Einstein and others to do so. But there has been progress in other directions: nuclear radioactivity and electromagnetism, it appears, are the result of the same underlying forces, the electro-weak force. Our detailed awareness of the overall unity seems to be expanding. As more and more is discovered about nature, more and more of it fits together.

This unity is a sentimental fruit of science more than it is an immediately practical one. It removes for us any sense of frivolous arbitrariness about the behavior of nature. This quest for unity, this reduction of the number of

different kinds of explanations or causes that are needed in order to account for observed diversity, started a long time ago - perhaps with the atomic postulates about matter conceived by Democritus and the Greeks.

A contrary trend is manifest in so-called “pseudoscience.” I have heard people claim that if they were in Fresno and had bad thoughts about the plants in their home in San Francisco, the plants would be wilted when they returned home. Such behavior on the part of the plants belies everything that I know about long-range action at a distance. No matter how often the experiment was repeated, I would not believe that there was any cause-and-effect relationship between the bad thoughts and the wilted plants.

At the Exploratorium we have tried to express this unity in two ways. We have set up the exhibits in sections—Electricity, Light, Animal Behavior, etc.—with each section showing multiple examples of a particular kind of behavior. But there are no walls between these sections. And exhibits on reflection, for example, occur in the Light, the Sound, and the Resonance sections.

In addition to our exhibits, our quarterly magazine, *The Exploratorium*, promotes the idea of unity. Each issue is about a single topic treated from several different points of view. The issue on bicycles, for example, had articles about their construction, their stability, their history and social impact, the most modern improvements and efficiency, etc. I believe that most of the science magazines do a disservice to the cause of science by including in each issue a hodge-podge of unrelated topics in the hope that they will attract more readers. In doing so they belie the important sense of unity that science can bring to all of us. The simplification of our view of the world that comes with understanding how things fit together may be one of the most important emotional and sentimental fruits of science.

The other sentimental fruit of science that I want to touch on briefly is a change in our view

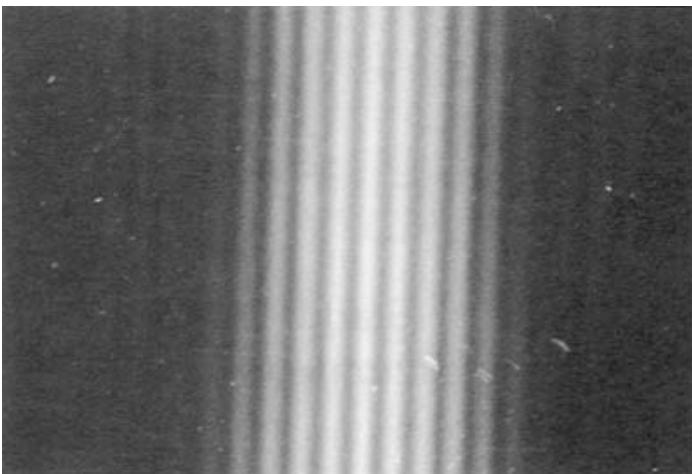
of heresy. This is a change that has developed during the twentieth century and that has had a very profound influence on the way that we think about nature. The change has come about through the study of the tiny scale of atomic and subatomic matter, of the huge scale of cosmology, and of the incredibly complex interlocking interactions encountered in biology. These are domains of nature in which the details are completely removed from our ordinary experience. The problems first appeared in the study of electrons and of light. A great list of experiments showed conclusively that electrons behaved like the particles and light like the waves of everyday experience: like BB shot on the one hand and water waves on the other. But an equally valid long list of newly performed experiments that asked questions in different contexts showed electrons behaved as do familiar waves and that, in other experiments, light arrived in small bundles of energy as does a BB pellet. It makes no sense whatsoever to say that light is both a wave and a particle, that it spreads out in all directions like a wave and also travels in one direction and lands in a certain spot with a splash! In some contexts, beams of electrons behave like waves and are waves; while in other well-defined experimental contexts, electrons behave like and are particles. Neither statement or view is a heresy.

There is a mathematics of electrons that can describe their behavior in these different contexts, but there is no way of making sense

of this duality of description that can be based on ordinary human experience. With people, there also appear dual descriptions that are contradictory and can only be valid descriptions when applied in very different contexts. There is no mathematics with which to bridge the gap between these dual descriptions, but our experience with electrons and light indicates that there must be bridges beyond our experience. For example, *neither* the statement “there is no purpose that is fulfilled by people” nor the statement “everything people decide to do is for a purpose” need be considered a heresy. From a cosmological point of view, there would not be any difference if there were no people in the universe. On the other hand, it is impossible to talk about human beings or to properly describe them or ourselves without using the idea of “purpose.” We are always (or almost always) doing things for a reason, even building Exploratoriums.

There are many other value dualities that apply to people, and to me it has made a profound difference in my thinking to know that such dualities are required even in describing inanimate nature. I can be reassured that thoroughly contradictory ethical statements need not, either one of them, be a heresy when applied in the appropriate contexts. This possibility does not imply that there are no ethics or distinctions of right from wrong, but it does imply that we can mollify some of the fiercest intellectual battles of the present and the past. We need to recognize the need for contradictory but equally valid descriptions of matters that are not and never have been part of human experience. By accepting this need of dual and incompatible descriptions, we have greatly simplified our view of ourselves as being embedded in a concordant view of nature. For this relief we can, in large part, thank Niels Bohr and those who worked along with him.

In conceiving the Exploratorium we have had these sentimental fruits of science in mind, but we do not present them as such. However, we have been doing things for a purpose. If nothing else, we have created a delightful



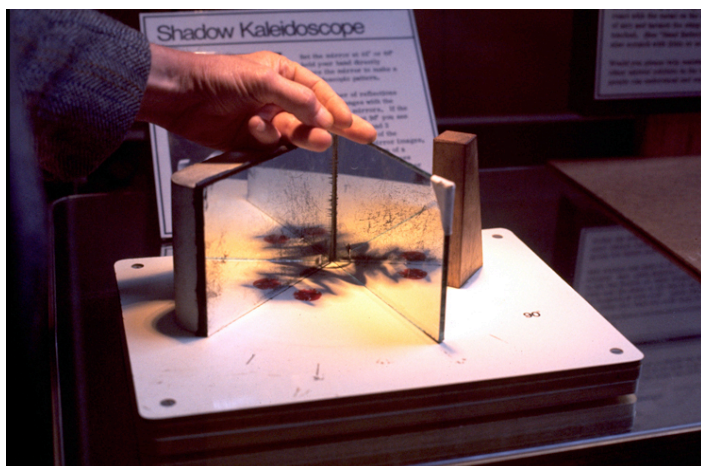
Electrons, when passed through a slit act as particles, not waves, in forming this diffraction pattern. Only waves can form this type of interference pattern.

woods whose “trees” are parts of nature, through which many people have had an opportunity to wander. We have also enabled people to understand these “woods” by their own exploring and by teaching each other.



that now, after a lifelong rejection of the subject, they could, in fact have understood it. The conveying to our visitors a sense that they can understand the things that are going on around them may be one of the more important things we do. This sense can then so readily extend to all aspects of people's lives. The intellectual apathy that I am told now exists among young people may have come about because these youths have never been convincingly taught the wonder of understanding or learned that when one does understand, then each person, as an individual or as a member of a group, can feel that they can make a difference. I do hope and think that we are contributing in this way.

Thank you.



Frank playing with one of his favorite exhibits, the Shadow Kaleidoscope.

If people feel they understand the world around them, or, probably, even if they have the conviction that they *could* understand it if they wanted to, then and only then are they also able to feel that they can make a difference through their decisions and activities. Without this conviction people usually live with the sense of being eternally pushed around by alien events and forces. I believe that the Exploratorium does help create or renew this conviction for very many people and that, especially for young people, it builds a desire to understand. I sense also that this is happening when I hear adult visitors tell me, “I wish that science had been taught this way when I was a kid.” What they are telling me is