Heretical thoughts about science and society

By Freeman Dyson, 8 July 2007

1. The Need for Heretics

In the modern world, science and society often interact in a perverse way. We live in a technological society, and technology causes political problems. The politicians and the public expect science to provide answers to the problems. Scientific experts are paid and encouraged to provide answers. The public does not have much use for a scientist who says, “Sorry, but we don’t know”. The public prefers to listen to scientists who give confident answers to questions and make confident predictions of what will happen as a result of human activities. So it happens that the experts who talk publicly about politically contentious questions tend to speak more clearly than they think. They make confident predictions about the future, and end up believing their own predictions. Their predictions become dogmas which they do not question. The public is led to believe that the fashionable scientific dogmas are true, and it may sometimes happen that they are wrong. That is why heretics who question the dogmas are needed.

As a scientist I do not have much faith in predictions. Science is organized unpredictability. The best scientists like to arrange things in an experiment to be as unpredictable as possible, and then they do the experiment to see what will happen. You might say that if something is predictable then it is not science. When I make predictions, I am not speaking as a scientist. I am speaking as a story-teller, and my predictions are science-fiction rather than science. The predictions of science-fiction writers are notoriously inaccurate. Their purpose is to imagine what might happen rather than to describe what will happen. I will be telling stories that challenge the prevailing dogmas of today. The prevailing dogmas may be right, but they still need to be challenged. I am proud to be a heretic. The world always needs heretics to challenge the prevailing orthodoxies. Since I am heretic, I am accustomed to being in the minority. If I could persuade everyone to agree with me, I would not be a heretic.

We are lucky that we can be heretics today without any danger of being burned at the stake. But unfortunately I am an old heretic. Old heretics do not cut much ice. When you hear an old heretic talking, you can always say, “Too bad he has lost his marbles”, and pass on. What the world needs is young heretics. I am hoping that one or two of the people who read this piece may fill that role.

Two years ago, I was at Cornell University celebrating the life of Tommy Gold, a famous astronomer who died at a ripe old age. He was famous as a heretic, promoting unpopular ideas that usually turned out to be right. Long ago I was a guinea-pig in Tommy’s experiments on human hearing. He had a heretical idea that the human ear discriminates pitch by means of a set of tuned resonators with active electromechanical feedback. He published a paper explaining how the ear must work, [Gold, 1948]. He described how the vibrations of the inner ear must be converted into electrical signals which feed back into the mechanical motion, reinforcing the vibrations and increasing the sharpness of the resonance. The experts in auditory physiology ignored his work because he did not have a degree in physiology. Many years later, the experts discovered the two kinds of hair-cells in the inner ear that actually do the feedback as Tommy had predicted, one kind of hair-cell acting as electrical sensors and the other kind acting as mechanical drivers. It took the experts forty years to admit that he was right. Of course, I knew that he was right, because I had helped him do the experiments.

Later in his life, Tommy Gold promoted another heretical idea, that the oil and natural gas in the ground come up from deep in the mantle of the earth and have nothing to do with biology. Again the experts are sure that he is wrong, and he did not live long enough to change their minds. Just a few weeks before he died, some chemists at the Carnegie Institution in Washington did a beautiful experiment in a diamond anvil cell, [Scott et al., 2004]. They mixed together tiny quantities of three things that we know exist in the mantle of the earth, and observed them at the pressure and temperature appropriate to the mantle about two hundred kilometers down. The three things were calcium carbonate which is sedimentary rock, iron oxide which is a component of igneous rock, and water. These three things are certainly present when a slab of subducted ocean floor descends from a deep ocean trench into the mantle. The experiment showed that they react quickly to produce lots of methane, which is natural gas. Knowing the result of the experiment, we can be sure that big quantities of natural gas exist in the mantle two hundred kilometers down. We do not know how much of this natural gas pushes its way up through cracks and channels in the overlying rock to form the shallow reservoirs of natural gas that we are now burning. If the gas moves up rapidly enough, it will arrive intact in the cooler regions where the reservoirs are found. If it moves too slowly through the hot region, the methane may be reconverted to carbonate rock and water. The Carnegie Institute experiment shows that there is at least a possibility that Tommy Gold was right and the natural gas reservoirs are fed from deep below. The chemists sent an E-mail to Tommy Gold to tell him their result, and got back a message that he had died three days earlier. Now that he is dead, we need more heretics to take his place.

2. Climate and Land Management

The main subject of this piece is the problem of climate change. This is a contentious subject, involving politics and economics as well as science. The science is inextricably mixed up with politics. Everyone agrees that the climate is changing, but there are violently diverging opinions about the causes of change, about the consequences of change, and about possible remedies. I am promoting a heretical opinion, the first of three heresies that I will discuss in this piece.

My first heresy says that all the fuss about global warming is grossly exaggerated. Here I am opposing the holy brotherhood of climate model experts and the crowd of deluded citizens who believe the numbers predicted by the computer models. Of course, they say, I have no degree in meteorology and I am therefore not qualified to speak. But I have studied the climate models and I know what they can do. The models solve the equations of fluid dynamics, and they do a very good job of describing the fluid motions of the atmosphere and the oceans. They do a very poor job of describing the clouds, the dust, the chemistry and the biology of fields and farms and forests. They do not begin to describe the real world that we live in. The real world is muddy and messy and full of things that we do not yet understand. It is much easier for a scientist to sit in an air-conditioned building and run computer models, than to put on winter clothes and measure what is really happening outside in the swamps and the clouds. That is why the climate model experts end up believing their own models.

There is no doubt that parts of the world are getting warmer, but the warming is not global. I am not saying that the warming does not cause problems. Obviously it does. Obviously we should be trying to understand it better. I am saying that the problems are grossly exaggerated. They take away money and attention from other problems that are more urgent and more important, such as poverty and infectious disease and public education and public health, and the preservation of living creatures on land and in the oceans, not to mention easy problems such as the timely construction of adequate dikes around the city of New Orleans.

I will discuss the global warming problem in detail because it is interesting, even though its importance is exaggerated. One of the main causes of warming is the increase of carbon dioxide in the atmosphere resulting from our burning of fossil fuels such as oil and coal and natural gas. To understand the movement of carbon through the atmosphere and biosphere, we need to measure a lot of numbers. I do not want to confuse you with a lot of numbers, so I will ask you to remember just one number. The number that I ask you to remember is one hundredth of an inch per year. Now I will explain what this number means. Consider the half of the land area of the earth that is not desert or ice-cap or city or road or parking-lot. This is the half of the land that is covered with soil and supports vegetation of one kind or another. Every year, it absorbs and converts into biomass a certain fraction of the carbon dioxide that we emit into the atmosphere. Biomass means living creatures, plants and microbes and animals, and the organic materials that are left behind when the creatures die and decay. We don't know how big a fraction of our emissions is absorbed by the land, since we have not measured the increase or decrease of the biomass. The number that I ask you to remember is the increase in thickness, averaged over one half of the land area of the planet, of the biomass that would result if all the carbon that we are emitting by burning fossil fuels were absorbed. The average increase in thickness is one hundredth of an inch per year.

The point of this calculation is the very favorable rate of exchange between carbon in the atmosphere and carbon in the soil. To stop the carbon in the atmosphere from increasing, we only need to grow the biomass in the soil by a hundredth of an inch per year. Good topsoil contains about ten percent biomass, [Schlesinger, 1977], so a hundredth of an inch of biomass growth means about a tenth of an inch of topsoil. Changes in farming practices such as no-till farming, avoiding the use of the plow, cause biomass to grow at least as fast as this. If we plant crops without plowing the soil, more of the biomass goes into roots which stay in the soil, and less returns to the atmosphere. If we use genetic engineering to put more biomass into roots, we can probably achieve much more rapid growth of topsoil. I conclude from this calculation that the problem of carbon dioxide in the atmosphere is a problem of land management, not a problem of meteorology. No computer model of atmosphere and ocean can hope to predict the way we shall manage our land.

Here is another heretical thought. Instead of calculating world-wide averages of biomass growth, we may prefer to look at the problem locally. Consider a possible future, with China continuing to develop an industrial economy based largely on the burning of coal, and the United States deciding to absorb the resulting carbon dioxide by increasing the biomass in our topsoil. The quantity of biomass that can be accumulated in living plants and trees is limited, but there is no limit to the quantity that can be stored in topsoil. To grow topsoil on a massive scale may or may not be practical, depending on the economics of farming and forestry. It is at least a possibility to be seriously considered, that China could become rich by burning coal, while the United States could become environmentally virtuous by accumulating topsoil, with transport of carbon from mine in China to soil in America provided free of charge by the atmosphere, and the inventory of carbon in the atmosphere remaining constant. We should take such possibilities into account when we listen to predictions about climate change and fossil fuels. If biotechnology takes over the planet in the next fifty years, as computer technology has taken it over in the last fifty years, the rules of the climate game will be radically changed.

When I listen to the public debates about climate change, I am impressed by the enormous gaps in our knowledge, the sparseness of our observations and the superficiality of our theories. Many of the basic processes of planetary ecology are poorly understood. They must be better understood before we can reach an accurate diagnosis of the present condition of our planet.

When we are trying to take care of a planet, just as when we are taking care of a human patient, diseases must be diagnosed before they can be cured. We need to observe and measure what is going on in the biosphere, rather than relying on computer models.

Everyone agrees that the increasing abundance of carbon dioxide in the atmosphere has two important consequences, first a change in the physics of radiation transport in the atmosphere, and second a change in the biology of plants on the ground and in the ocean. Opinions differ on the relative importance of the physical and biological effects, and on whether the effects, either separately or together, are beneficial or harmful. The physical effects are seen in changes of rainfall, cloudiness, wind-strength and temperature, which are customarily lumped together in the misleading phrase "global warming". In humid air, the effect of carbon dioxide on radiation transport is unimportant because the transport of thermal radiation is already blocked by the much larger greenhouse effect of water vapor. The effect of carbon dioxide is important where the air is dry, and air is usually dry only where it is cold. Hot desert air may feel dry but often contains a lot of water vapor. The warming effect of carbon dioxide is strongest where air is cold and dry, mainly in the arctic rather than in the tropics, mainly in mountainous regions rather than in lowlands, mainly in winter rather than in summer, and mainly at night rather than in daytime. The warming is real, but it is mostly making cold places warmer rather than making hot places hotter. To represent this local warming by a global average is misleading.

The fundamental reason why carbon dioxide in the atmosphere is critically important to biology is that there is so little of it. A field of corn growing in full sunlight in the middle of the day uses up all the carbon dioxide within a meter of the ground in about five minutes. If the air were not constantly stirred by convection currents and winds, the corn would stop growing. About a tenth of all the carbon dioxide in the atmosphere is converted into biomass every summer and given back to the atmosphere every fall. That is why the effects of fossil-fuel burning cannot be separated from the effects of plant growth and decay. There are five reservoirs of carbon that are biologically accessible on a short time-scale, not counting the carbonate rocks and the deep ocean which are only accessible on a time-scale of thousands of years. The five accessible reservoirs are the atmosphere, the land plants, the topsoil in which land plants grow, the surface layer of the ocean in which ocean plants grow, and our proved reserves of fossil fuels. The atmosphere is the smallest reservoir and the fossil fuels are the largest, but all five reservoirs are of comparable size. They all interact strongly with one another. To understand any of them, it is necessary to understand all of them.

As an example of the way different reservoirs of carbon dioxide may interact with each other, consider the atmosphere and the topsoil. Greenhouse experiments show that many plants growing in an atmosphere enriched with carbon dioxide react by increasing their root-to-shoot ratio. This means that the plants put more of their growth into roots and less into stems and leaves. A change in this direction is to be expected, because the plants have to maintain a balance between the leaves collecting carbon from the air and the roots collecting mineral nutrients from the soil. The enriched atmosphere tilts the balance so that the plants need less leaf-area and more root-area. Now consider what happens to the roots and shoots when the growing season is over, when the leaves fall and the plants die. The new-grown biomass decays and is eaten by fungi or microbes. Some of it returns to the atmosphere and some of it is converted into topsoil. On the average, more of the above-ground growth will return to the atmosphere and more of the below-ground growth will become topsoil. So the plants with increased root-to-shoot ratio will cause an increased transfer of carbon from the atmosphere into topsoil. If the increase in atmospheric carbon dioxide due to fossil-fuel burning has caused an increase in the average root-to-shoot ratio of plants over large areas, then the possible effect on the top-soil reservoir will not be small. At present we have no way to measure or even to guess the size of this effect. The aggregate biomass of the topsoil of the planet is not a measurable quantity. But the fact that the topsoil is unmeasurable does not mean that it is unimportant.

At present we do not know whether the topsoil of the United States is increasing or decreasing. Over the rest of the world, because of large-scale deforestation and erosion, the topsoil reservoir is probably decreasing. We do not know whether intelligent land-management could increase the growth of the topsoil reservoir by four billion tons of carbon per year, the amount needed to stop the increase of carbon dioxide in the atmosphere. All that we can say for sure is that this is a theoretical possibility and ought to be seriously explored.

3. Oceans and Ice-ages

Another problem that has to be taken seriously is a slow rise of sea level which could become catastrophic if it continues to accelerate. We have accurate measurements of sea level going back two hundred years. We observe a steady rise from 1800 to the present, with an acceleration during the last fifty years. It is widely believed that the recent acceleration is due to human activities, since it coincides in time with the rapid increase of carbon dioxide in the atmosphere. But the rise from 1800 to 1900 was probably not due to human activities. The scale of industrial activities in the nineteenth century was not large enough to have had measurable global effects. So a large part of the observed rise in sea level must have other causes. One possible cause is a slow readjustment of the shape of the earth to the disappearance of the northern ice-sheets at the end of the ice age twelve thousand years ago. Another possible cause is the large-scale melting of glaciers, which also began long before human influences on climate became significant. Once again, we have an environmental danger whose magnitude cannot be predicted until we know more about its causes, [Munk, 2002].

The most alarming possible cause of sea-level rise is a rapid disintegration of the West Antarctic ice-sheet, which is the part of Antarctica where the bottom of the ice is far below sea level. Warming seas around the edge of Antarctica might erode the ice-cap from below and cause it to collapse into the ocean. If the whole of West Antarctica disintegrated rapidly, sea-level would rise by five meters, with disastrous effects on billions of people. However, recent measurements of the ice-cap show that it is not losing volume fast enough to make a significant contribution to the presently observed sea-level rise. It appears that the warming seas around Antarctica are causing an increase in snowfall over the ice-cap, and the increased snowfall on top roughly cancels out the decrease of ice volume caused by erosion at the edges. The same changes, increased melting of ice at the edges and increased snowfall adding ice on top, are also observed in Greenland. In addition, there is an increase in snowfall over the East Antarctic Ice-cap, which is much larger and colder and is in no danger of melting. This is another situation where we do not know how much of the environmental change is due to human activities and how much to long-term natural processes over which we have no control.

Another environmental danger that is even more poorly understood is the possible coming of a new ice-age. A new ice-age would mean the burial of half of North America and half of Europe under massive ice-sheets. We know that there is a natural cycle that has been operating for the last eight hundred thousand years. The length of the cycle is a hundred thousand years. In each hundred-thousand year period, there is an ice-age that lasts about ninety thousand years and a warm interglacial period that lasts about ten thousand years. We are at present in a warm period that began twelve thousand years ago, so the onset of the next ice-age is overdue. If human activities were not disturbing the climate, a new ice-age might already have begun. We do not know how to answer the most important question: do our human activities in general, and our burning of fossil fuels in particular, make the onset of the next ice-age more likely or less likely?

There are good arguments on both sides of this question. On the one side, we know that the level of carbon dioxide in the atmosphere was much lower during past ice-ages than during warm periods, so it is reasonable to expect that an artificially high level of carbon dioxide might stop an ice-age from beginning. On the other side, the oceanographer Wallace Broecker [Broecker, 1997] has argued that the present warm climate in Europe depends on a circulation of ocean water, with the Gulf Stream flowing north on the surface and bringing warmth to Europe, and with a counter-current of cold water flowing south in the deep ocean. So a new ice-age could begin whenever the cold deep counter-current is interrupted. The counter-current could be interrupted when the surface water in the Arctic becomes less salty and fails to sink, and the water could become less salty when the warming climate increases the Arctic rainfall. Thus Broecker argues that a warm climate in the Arctic may paradoxically cause an ice-age to begin. Since we are confronted with two plausible arguments leading to opposite conclusions, the only rational response is to admit our ignorance. Until the causes of ice-ages are understood, we cannot know whether the increase of carbon-dioxide in the atmosphere is increasing or decreasing the danger.

4. The Wet Sahara

My second heresy is also concerned with climate change. It is about the mystery of the wet Sahara. This is a mystery that has always fascinated me. At many places in the Sahara desert that are now dry and unpopulated, we find rock-paintings showing people with herds of animals. The paintings are abundant, and some of them are of high artistic quality, comparable with the more famous cave-paintings in France and Spain. The Sahara paintings are more recent than the cave-paintings. They come in a variety of styles and were probably painted over a period of several thousand years. The latest of them show Egyptian influences and may be contemporaneous with early Egyptian tomb paintings. Henri Lhote’s book, “The Search for the Tassili Frescoes”, [Lhote, 1958], is illustrated with reproductions of fifty of the paintings. The best of the herd paintings date from roughly six thousand years ago. They are strong evidence that the Sahara at that time was wet. There was enough rain to support herds of cows and giraffes, which must have grazed on grass and trees. There were also some hippopotamuses and elephants. The Sahara then must have been like the Serengeti today.

At the same time, roughly six thousand years ago, there were deciduous forests in Northern Europe where the trees are now conifers, proving that the climate in the far north was milder than it is today. There were also trees standing in mountain valleys in Switzerland that are now filled with famous glaciers. The glaciers that are now shrinking were much smaller six thousand years ago than they are today. Six thousand years ago seems to have been the warmest and wettest period of the interglacial era that began twelve thousand years ago when the last Ice Age ended. I would like to ask two questions. First, if the increase of carbon dioxide in the atmosphere is allowed to continue, shall we arrive at a climate similar to the climate of six thousand years ago when the Sahara was wet? Second, if we could choose between the climate of today with a dry Sahara and the climate of six thousand years ago with a wet Sahara, should we prefer the climate of today? My second heresy answers yes to the first question and no to the second. It says that the warm climate of six thousand years ago with the wet Sahara is to be preferred, and that increasing carbon dioxide in the atmosphere may help to bring it back. I am not saying that this heresy is true. I am only saying that it will not do us any harm to think about it.

The biosphere is the most complicated of all the things we humans have to deal with. The science of planetary ecology is still young and undeveloped. It is not surprising that honest and well-informed experts can disagree about facts. But beyond the disagreement about facts, there is another deeper disagreement about values. The disagreement about values may be described in an over-simplified way as a disagreement between naturalists and humanists. Naturalists believe that nature knows best. For them the highest value is to respect the natural order of things. Any gross human disruption of the natural environment is evil. Excessive burning of fossil fuels is evil. Changing nature's desert, either the Sahara desert or the ocean desert, into a managed ecosystem where giraffes or tunafish may flourish, is likewise evil. Nature knows best, and anything we do to improve upon Nature will only bring trouble.

The humanist ethic begins with the belief that humans are an essential part of nature. Through human minds the biosphere has acquired the capacity to steer its own evolution, and now we are in charge. Humans have the right and the duty to reconstruct nature so that humans and biosphere can both survive and prosper. For humanists, the highest value is harmonious coexistence between humans and nature. The greatest evils are poverty, underdevelopment, unemployment, disease and hunger, all the conditions that deprive people of opportunities and limit their freedoms. The humanist ethic accepts an increase of carbon dioxide in the atmosphere as a small price to pay, if world-wide industrial development can alleviate the miseries of the poorer half of humanity. The humanist ethic accepts our responsibility to guide the evolution of the planet.

The sharpest conflict between naturalist and humanist ethics arises in the regulation of genetic engineering. The naturalist ethic condemns genetically modified food-crops and all other genetic engineering projects that might upset the natural ecology. The humanist ethic looks forward to a time not far distant, when genetically engineered food-crops and energy-crops will bring wealth to poor people in tropical countries, and incidentally give us tools to control the growth of carbon dioxide in the atmosphere. Here I must confess my own bias. Since I was born and brought up in England, I spent my formative years in a land with great beauty and a rich ecology which is almost entirely man-made. The natural ecology of England was uninterrupted and rather boring forest. Humans replaced the forest with an artificial landscape of grassland and moorland, fields and farms, with a much richer variety of plant and animal species. Quite recently, only about a thousand years ago, we introduced rabbits, a non-native species which had a profound effect on the ecology. Rabbits opened glades in the forest where flowering plants now flourish. There is no wilderness in England, and yet there is plenty of room for wild-flowers and birds and butterflies as well as a high density of humans. Perhaps that is why I am a humanist.

To conclude this piece I come to my third and last heresy. My third heresy says that the United States has less than a century left of its turn as top nation. Since the modern nation-state was invented around the year 1500, a succession of countries have taken turns at being top nation, first Spain, then France, Britain, America. Each turn lasted about 150 years. Ours began in 1920, so it should end about 2070. The reason why each top nation's turn comes to an end is that the top nation becomes over-extended, militarily, economically and politically. Greater and greater efforts are required to maintain the number one position. Finally the over-extension becomes so extreme that the structure collapses. Already we can see in the American posture today some clear symptoms of over-extension. Who will be the next top nation? China is the obvious candidate. After that it might be India or Brazil. We should be asking ourselves, not how to live in an America-dominated world, but how to prepare for a world that is not America-dominated. That may be the most important problem for the next generation of Americans to solve. How does a people that thinks of itself as number one yield gracefully to become number two?

I am telling the next generation of young students, who will still be alive in the second half of our century, that misfortunes are on the way. Their precious Ph.D., or whichever degree they went through long years of hard work to acquire, may be worth less than they think. Their specialized training may become obsolete. They may find themselves over-qualified for the available jobs. They may be declared redundant. The country and the culture to which they belong may move far away from the mainstream. But these misfortunes are also opportunities. It is always open to them to join the heretics and find another way to make a living. With or without a Ph.D., there are big and important problems for them to solve.

I will not attempt to summarize the lessons that my readers should learn from these heresies. The main lesson that I would like them to take home is that the long-range future is not predetermined. The future is in their hands. The rules of the world-historical game change from decade to decade in unpredictable ways. All our fashionable worries and all our prevailing dogmas will probably be obsolete in fifty years. My heresies will probably also be obsolete. It is up to them to find new heresies to guide our way to a more hopeful future.

5. Bad Advice to a Young Scientist

Sixty years ago, when I was a young and arrogant physicist, I tried to predict the future of physics and biology. My prediction was an extreme example of wrongness, perhaps a world record in the category of wrong predictions. I was giving advice about future employment to Francis Crick, the great biologist who died in 2005 after a long and brilliant career. He discovered, with Jim Watson, the double helix. They discovered the double helix structure of DNA in 1953, and thereby gave birth to the new science of molecular genetics. Eight years before that, in 1945, before World War 2 came to an end, I met Francis Crick for the first time. He was in Fanum House, a dismal office building in London where the Royal Navy kept a staff of scientists. Crick had been working for the Royal Navy for a long time and was depressed and discouraged. He said he had missed his chance of ever amounting to anything as a scientist. Before World War 2, he had started a promising career as a physicist. But then the war hit him at the worst time, putting a stop to his work in physics and keeping him away from science for six years. The six best years of his life, squandered on naval intelligence, lost and gone forever. Crick was good at naval intelligence, and did important work for the navy. But military intelligence bears the same relation to intelligence as military music bears to music. After six years doing this kind of intelligence, it was far too late for Crick to start all over again as a student and relearn all the stuff he had forgotten. No wonder he was depressed. I came away from Fanum House thinking, “How sad. Such a bright chap. If it hadn’t been for the war, he would probably have been quite a good scientist”.

A year later, I met Crick again. The war was over and he was much more cheerful. He said he was thinking of giving up physics and making a completely fresh start as a biologist. He said the most exciting science for the next twenty years would be in biology and not in physics. I was then twenty-two years old and very sure of myself. I said, “No, you’re wrong. In the long run biology will be more exciting, but not yet. The next twenty years will still belong to physics. If you switch to biology now, you will be too old to do the exciting stuff when biology finally takes off". Fortunately, he didn't listen to me. He went to Cambridge and began thinking about DNA. It took him only seven years to prove me wrong. The moral of this story is clear. Even a smart twenty-two-year-old is not a reliable guide to the future of science. And the twenty-two-year-old has become even less reliable now that he is eighty-two.