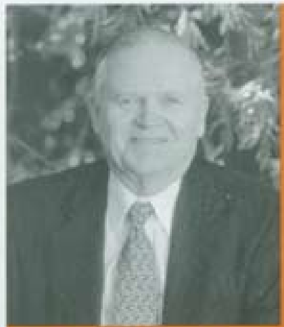
HERETICAL THOUGHTS
ABOUT SCIENCE *and* SOCIETY

By Freeman Dyson

FREDERICK S. PARDEE
DISTINGUISHED LECTURE

November 1, 2005

The Pardee Center
Distinguished Lecture Series



Frederick S. Pardee

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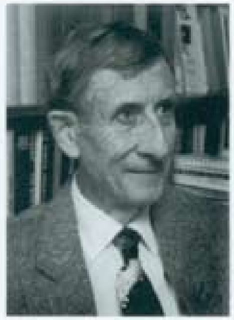

Freeman Dyson is Professor Emeritus of Physics at the Institute for Advanced Study in Princeton, New Jersey. He was born in England and worked as a civilian scientist for the Royal Air Force in World War II. He graduated from Cambridge University in 1945 with a B.A. degree in mathematics. He went on to Cornell University as a graduate student in 1947 and worked with Hans Bethe and Richard Feynman. His most useful contribution to science was the unification of the three versions of quantum electrodynamics invented by Feynman, Schwinger, and Tomonaga. Cornell University made him a professor without bothering about his lack of a Ph.D. He subsequently worked on nuclear reactors, solid state physics, ferromagnetism, astrophysics, and biology, looking for problems where elegant mathematics could be usefully applied. He has written a number of books about science for the general public. *Disturbing the Universe* (1974) is a portrait-gallery of people he has known during his career as a scientist. *Weapons of Hope* (1984) is a study of ethical problems of war and peace. *Infinite in All Directions* (1988) is a philosophical meditation based on Dyson's Gifford Lectures on Natural Theology given at the University of Aberdeen in Scotland. *Origins of Life* (1986, second edition 1999) is a study of one of the major unsolved problems of science. *The Sun, the Genome and the Internet* (1999) discusses the question of whether modern technology could be used to narrow the gap between rich and poor rather than widen it. Dyson is a fellow of the American Physical Society, a member of the U.S. National Academy of Sciences, and a fellow of the Royal Society of London. In 2000 he was awarded the Templeton Prize for Progress in Religion.

Heretical Thoughts about Science and Society

I am grateful to Boston University, and to Mr. Frederick Pardee in particular, for inviting me here to talk about the longer-range future. Mr. Pardee has defined what he means by the longer-range future. It is the future from thirty-five to two hundred years ahead. I will try to stay within those limits. But I should say at the start that as a scientist I do not have much faith in predictions. Science is organized unpredictably. What scientists do is to arrange things in an experiment to be as unpredictable as possible, and then do the experiment to see what will happen. You might say that if something is predictable then it is not science. So, when I am making predictions, I am not speaking as a scientist. This evening I will be speaking as a storyteller, and my predictions will be 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. My purpose is to tell some 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 stories that I shall tell are heresies, numbered from one to six.

The world always needs heretics to challenge the prevailing orthodoxies. 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 you people in the audience may fill that role.

A few months 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. 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. It took the experts forty years to admit that he was right. Of course, I knew that he was right, because I had seen him do the experiments. Later in his life, he 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. But just a few months ago, some chemists at the Carnegie Institution in Washington did a beautiful experiment in a diamond anvil cell. 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 shows that they react quickly to produce lots of methane, which is natural gas. So, big quantities of natural gas certainly exist in the mantle. 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.

In this talk I am promoting six heresies. My first 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 took turns at being top nation, first Spain, then France, Britain, America. Each turn lasted about one hundred fifty 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. You should be asking yourselves, 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 you that misfortunes are on the way. Your precious Ph.D., or whichever degree you went through long years of hard work to acquire, may be worth less than you think. Your specialized training may become obsolete. You may find yourself over-qualified for the available jobs. You may be declared redundant. The country and the culture to which you belong may move far away from the mainstream. But these misfortunes are also opportunities. It is always open to you 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 you to solve.

My second heresy will take longer to explain and discuss. It 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 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.

Land Management and Climate

I will talk about the global warming problem because it is interesting, even though its importance is exaggerated. To understand the movement of carbon through the atmosphere and biosphere in detail, 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. We don't know how big a fraction it absorbs, 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 worldwide 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 genetically engineered crop plants. 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 mines 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.

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 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 abundance 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 timescale, not counting the carbonate rocks and the deep ocean which are only accessible on a timescale 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 net 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 topsoil 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.

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 is 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, the 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. There is also 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 one 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. The big question that we do not know how to answer is, 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.

The Wet Sahara

My third heresy 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 (Lhote 1958). The paintings are abundant and of amazing 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 must be contemporaneous with early Egyptian tomb paintings. Henri Lhote's book, *The Search for the Tassili Frescoes*, has marvelous 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 third 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 disagreements 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 naturalist ethic is the driving force behind the Kyoto Protocol.

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, under-development, 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 worldwide 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 conclude by confessing 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 wildflowers and birds and butterflies as well as a high density of humans. Perhaps that is why I am a humanist.

The Domestication of Biotechnology

My fourth heresy is about the domestication of biotechnology. I am serving on a committee of the National Academy of Sciences with the ponderous name, Committee on Advances in Technology and the Prevention of Their Application to Next Generation Biowarfare Threats. We discuss with all due seriousness the doomsday scenarios that biological weapons and other abuses of biotechnology may bring about. The following remarks are taken from a paper that I wrote for the committee, to lighten the tone of our discussions. I am not expecting the committee to agree with it, and I am not expecting it to appear as part of our official report.

> Fifty years ago in Princeton, I watched the mathematician John von Neumann designing and building the first electronic computer that operated with instructions coded into the machine. Von Neumann did not invent the electronic computer. The computer called ENIAC had been running at the University of Pennsylvania five years earlier. What von Neumann invented was software, the coded instructions that gave the computer agility and flexibility. It was the combination of electronic hardware with punch-card software that allowed a single machine to predict weather, to simulate the evolution of populations of living creatures, and to test the feasibility of hydrogen bombs. Von Neumann understood that his invention would change the world. He understood that the descendants of his machine would dominate the operations of science and business and government. But he imagined computers always remaining large and expensive. He imagined them as centralized facilities serving large research laboratories or large industries. He failed to foresee computers growing small enough and cheap enough to be used by housewives for doing income-tax returns or by kids for doing homework. He failed to foresee the final domestication of computers as toys for three-year-olds. He totally failed to foresee the emergence of computer games as a dominant feature of twenty-first-century life. Because

of computer games, our grandchildren are now growing up with an indelible addiction to computers. For better or for worse, in sickness or in health, till death do us part, humans and computers are now joined together more durably than husbands and wives.

What has this story of von Neumann's computer and the evolution of computer games to do with biotechnology? Simply this, that there is a close analogy between von Neumann's vision of computers as large, centralized facilities and the public perception of genetic engineering today as an activity of large pharmaceutical and agribusiness corporations such as Monsanto. The public distrusts Monsanto because Monsanto likes to put genes for poisonous pesticides into food crops, just as we distrusted von Neumann because von Neumann liked to use his computer for designing hydrogen bombs. It is likely that genetic engineering will remain unpopular and controversial so long as it remains a centralized activity in the hands of large corporations.

I see a bright future for the biotechnical industry when it follows the path of the computer industry, the path that von Neumann failed to foresee, becoming small and domesticated rather than big and centralized. The first step in this direction was already taken recently, when genetically modified tropical fish with new and brilliant colors appeared in pet stores. For biotechnology to become domesticated, the next step is to become user-friendly. I recently spent a happy day at the Philadelphia Flower Show, the biggest flower show in the world, where flower breeders from all over the world show off the results of their efforts. I have also visited the Reptile Show in San Diego, an equally impressive show displaying the work of another set of breeders. Philadelphia excels in orchids and roses, San Diego excels in lizards and snakes. The main problem for a grandparent visiting the reptile show with a grandchild is to get the grandchild out of the building without actually buying a snake. Every orchid or rose or lizard or snake is the work of a dedicated and skilled breeder. There are thousands of people, amateurs and professionals, who devote their lives to this business. Now imagine what will happen when the tools of genetic engineering become accessible to these people. There will be do-it-yourself kits for gardeners who will use genetic engineering to breed new varieties of roses and orchids. Also kits for lovers of pigeons and parrots

and lizards and snakes to breed new varieties of pets. Breeders of dogs and cats will have their kits too.

Genetic engineering, once it gets into the hands of housewives and children, will give us an explosion of diversity of new living creatures, rather than the monoculture crops that the big corporations prefer. New lineages will proliferate to replace those that monoculture farming and industrial development have destroyed. Designing genomes will be a personal thing, a new art form as creative as painting or sculpture. Few of the new creations will be masterpieces, but all will bring joy to their creators and variety to our fauna and flora.

The final step in the domestication of biotechnology will be biotech games, designed like computer games for children down to kindergarten age, but played with real eggs and seeds rather than with images on a screen. Playing such games, kids will acquire an intimate feeling for the organisms that they are growing. The winner could be the kid whose seed grows the prickliest cactus, or the kid whose egg hatches the cutest dinosaur. These games will be messy and possibly dangerous. Rules and regulations will be needed to make sure that our kids do not endanger themselves and others.

If domestication of biotechnology is the wave of the future, five important questions need to be answered. First, can it be stopped? Second, ought it to be stopped? Third, if stopping it is either impossible or undesirable, what are the appropriate limits that our society must impose on it? Fourth, how should the limits be decided? Fifth, how should the limits be enforced, nationally and internationally? In considering each of these questions, it would be helpful to keep in mind the analogy between computer technology and biotechnology. The majority of people using domesticated biotechnology to cause trouble will probably be small fry, like the young computer hackers who spread computer viruses around on the internet. On the other hand, there is a big difference between a computer virus and a real virus like influenza or HIV. If we allow kids to play around with roses and snakes, we still have to stop them from playing around with viruses.

My fifth heresy was suggested by a meeting that I attended recently in the city of Portland, Oregon. The meeting was called OSCON, short for Open Source Convention. It was a meeting organized by a group of people who call themselves the Geek Culture. A lot of them are people who dropped out of college and started software companies. There were about a thousand geeks at the meeting, mostly young and adventurous and interested in other things besides getting rich. Their companies are based on software programs that are out in the open like UNIX and LINUX, free for anyone to copy and improve. They share an intense dislike for companies like Microsoft which keep their source code secret. They despise people who won't share.

I talked to the Open Source crowd about biological sharing. In addition to sharing genome databases, biological communities can also share genes. The physical sharing of genes between diverse members of a community gives another meaning to the phrase Open Source. When genes are shared freely, a biological community reaps the same advantages from sharing genes as the Open Source community reaps from sharing software. My fifth heresy says that the Open Source movement may be recapitulating in a few decades the history of life on earth over billions of years.

Carl Woese is the world's greatest expert in the field of microbial taxonomy. He explored the ancestry of microbes by tracing the similarities and differences between their genomes. He discovered the large-scale structure of the tree of life, with all living creatures descended from three primordial branches. He recently published a provocative and illuminating article (Woese 2004) with the title, "A New Biology for a New Century," in the June 2004 issue of *Microbiology and Molecular Biology Reviews*. His main theme is the obsolescence of reductionist biology as it has been practiced for the last hundred years, and the need for a new synthetic biology based on communities and ecosystems rather than on genes and molecules. Aside from his main theme, he raises another profoundly important question: When did Darwinian evolution begin? By Darwinian evolution he means evolution as Darwin understood it, based on the competition for survival of non-interbreeding species. He presents evidence that Darwinian evolution did not go back to the beginning of life. The comparison of genomes of ancient lineages of living creatures shows evidence of massive transfers of genetic information from one lineage to another. In early times, the process that he calls Horizontal Gene Transfer, the sharing of genes between unrelated species, was prevalent. It becomes more prevalent the further back you go in time.

Whatever Carl Woese writes, even in a speculative vein, needs to be taken seriously. In his "New Biology" article, he is postulating a golden age of pre-Darwinian life, when horizontal gene transfer was universal and separate species did not exist. Life was then a community of cells of various kinds, sharing their genetic information so that clever chemical tricks and catalytic processes invented by one creature could be inherited by all of them. Evolution was a communal affair, the whole community advancing in metabolic and reproductive efficiency as the genes of the most efficient cells were shared. Evolution could be rapid, as new chemical devices could be evolved simultaneously by cells of different kinds working in parallel and then reassembled in a single cell by horizontal gene transfer. But then, one evil day, a cell resembling a primitive bacterium happened to find itself one jump ahead of its neighbors in efficiency. That cell, anticipating Bill Gates by three billion years, separated itself from the community and refused to share. Its offspring became the first species, reserving its intellectual property for its own private use. With its superior efficiency it continued to prosper and to evolve separately, while the rest of the community continued its communal life. Some millions of years later, another cell separated itself from the community and became another species. And so it went on, until nothing was left of the community and all life was divided into species. The Darwinian interlude had begun.

Now, after three billion years, the Darwinian interlude is over. It was an interlude between two periods of horizontal gene transfer. The epoch of Darwinian evolution based on competition between species ended about ten thousand years ago when a single species, *Homo sapiens*, began to dominate and reorganize the biosphere. Since that time, cultural evolution has replaced biological evolution as the main driving force of change. Cultural evolution is not Darwinian. Cultures spread by horizontal transfer of ideas more than by genetic inheritance. Cultural evolution is running a thousand times faster than Darwinian evolution, taking us into a new era of cultural interdependence which we call globalization. And now, in the last thirty years, *Homo sapiens* has revived the ancient pre-Darwinian practice of horizontal gene transfer, moving genes easily from microbes to plants and animals, blurring the boundaries between species. We are moving rapidly into the post-Darwinian era, when species will no longer exist, Open Source principles will govern the exchange of genes, and the evolution of life will again be communal. That is my fifth heresy.

Rural Poverty

My sixth and last heresy is about rural poverty. Rural poverty is one of the great evils of the modern world. The lack of jobs and economic opportunities in villages drives millions of people to migrate from villages into overcrowded cities. The continuing migration causes immense social and environmental problems in the major cities of poor countries. The effects of poverty are most visible in the cities, but the causes of poverty lie mostly in the villages. What the world needs is a technology that directly attacks the problem of rural poverty by creating wealth and jobs in the villages. A technology that creates industries and careers in villages would give the villagers a practical alternative to migration. It would give them a chance to survive and prosper without uprooting themselves.

The shifting balance of wealth and population between villages and cities is one of the main themes of human history over the last ten thousand years. The shift from villages to cities is strongly coupled with a shift from one kind of technology to another. I find it convenient to call the two kinds of technology green and grey. The adjective green has been appropriated and abused by various political movements, especially in Europe, so I need to explain clearly what I have in mind when I speak of green and grey. Green technology is based on biology, grey technology on physics and chemistry. Roughly speaking, green technology is the technology that gave birth to village communities ten thousand years ago, starting from the domestication of plants and animals, the invention of agriculture, the breeding of goats and sheep and cows and pigs, the manufacture of textiles and cheese and wine. Grey technology is the technology that gave birth to cities and empires five thousand years later, starting from the forging of bronze and iron, the invention of wheeled vehicles and paved roads, the building of ships and war chariots, the manufacture of swords and guns and bombs. For the first five of the ten thousand years, wealth and power belonged to villages with green technology, and for the second five thousand years wealth and power belonged to cities with grey technology. Beginning about five hundred years ago, grey technology became increasingly dominant, as we learned to build machines using power from wind and water and steam and electricity. In the last hundred years, wealth and power were even more heavily concentrated in cities as grey technology raced ahead. As cities became richer, rural poverty deepened.

This sketch of the last ten thousand years of human history puts the problem of rural poverty into a new perspective. My sixth heresy says

that green technology could give us a cure for rural poverty. If rural poverty is a consequence of the unbalanced growth of grey technology, it is possible that a shift in the balance back from grey to green might cause rural poverty to disappear. That is my dream. During the last fifty years we have seen explosive progress in the scientific understanding of the basic processes of life, and in the last twenty years this new understanding has given rise to explosive growth of green technology. The new green technology allows us to breed new varieties of animals and plants as our ancestors did ten thousand years ago, but now a hundred times faster, taking a decade instead of a millennium to create a new crop plant. Guided by a precise understanding of genes and genomes instead of by trial and error, we can within a few years modify plants so as to give them improved yield, improved nutritive value, or improved resistance to pests and diseases.

Within a few more decades, as the continued exploring of genomes gives us more complete knowledge of the architecture of living creatures, we shall be able to design new varieties of microbes and plants according to our needs. The way will then be open for green technology to do more cheaply and more cleanly many of the things that grey technology can do, and also to do many things that grey technology has failed to do. Green technology could replace most of our existing chemical industries and a large part of our mining and manufacturing industries. Green technology could achieve a more complete recycling of waste products and worn-out machines, with great benefit to the environment. An economic system based on green technology could come much closer to the goal of sustainability, using sunlight instead of fossil fuels as the primary source of energy. New species of termite could be engineered to chew up derelict automobiles instead of houses, and new species of tree with silicon leaves could convert carbon dioxide and sunlight into liquid fuels instead of cellulose.

Before genetically modified termites and trees can be allowed to help solve our economic and environmental problems, great arguments will rage over the possible damage they may do. Many of the people who call themselves green are passionately opposed to green technology. But in the end, if the technology is developed carefully and deployed with sensitivity to human feelings, it is likely to be accepted by most of the people who will be affected by it, just as the equally unnatural and unfamiliar green technologies of milking cows and plowing soils and fermenting grapes were accepted by our ancestors long ago. I am not saying that the political acceptance of green technology will be quick or easy. I say only that green technology has enormous promise for preserving the balance of nature on this planet as well as for relieving human misery.

Future generations of people raised from childhood with biotech toys and games will probably accept it more easily than we do. Nobody can predict how long it may take to try out the new technology in a thousand different ways and measure its costs and benefits.

What has this dream of a resurgent green technology to do with the problem of rural poverty? In the past, green technology has always been rural, based in farms and villages rather than in cities. In the future it will pervade cities as well as countryside, factories as well as forests. It will not be entirely rural. But it will still have a large rural component. After all, the cloning of Dolly occurred in a rural animal-breeding station in Scotland, not in an urban laboratory in Silicon Valley. Green technology will use land and sunlight as its primary sources of raw materials and energy. Land and sunlight cannot be concentrated in cities but are spread more or less evenly over the planet. When industries and technologies are based on land and sunlight, they will bring employment and wealth to rural populations. It is fortunate that sunlight is most abundant in tropical countries where a large fraction of the world's people live and where rural poverty is most acute. Since sunlight is distributed more equitably than coal and oil, green technology can be a great equalizer, helping to narrow the gap between rich and poor countries.

Six years ago I published a book with the title *The Sun, the Genome and the Internet* describing a vision of green technology enriching villages all over the world and halting the migration from villages to megacities (Dyson 1999). The three components of the vision are all essential, the Sun to provide energy where it is needed, the genome to provide plants which can convert sunlight into chemical fuels cheaply and efficiently, the Internet to end the intellectual and economic isolation of rural populations. With all three components in place, every village in Africa could enjoy its fair share of the blessings of civilization. People who prefer to live in cities would still be free to move from villages to cities, but they would not be compelled to move by economic necessity.

My time is now at an end, and I will not attempt to summarize the lessons that you may have learned from these six heresies. The main lesson that I would like you to take home is that the long-range future is not predetermined. The future is in your 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 less than thirty-five years. My heresies will probably also be obsolete. It is up to you to find new heresies to guide our way to a more hopeful future. I would like to end by borrowing a conclusion from my friend,

the astronomer Subrahmanyan Chandrasekhar (Chandrasekhar 1987), who borrowed it from the epilogue to Shakespeare's *Henry IV Part II:*

> First, my fear; then my courtesy; last my speech.
> My fear is, your displeasure; my courtesy, my duty;
> and my speech, to beg your pardons.

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