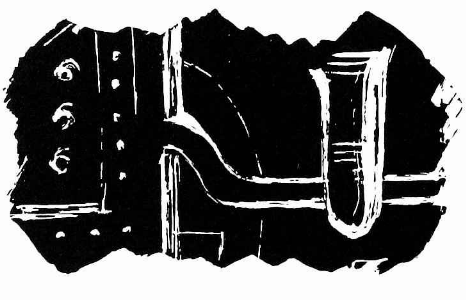
THE NEXT INDUSTRIAL REVOLUTION by Freeman J. Dyson

Industrial revolutions are unpopular these days. In the United States many people woke up only recently to the bad effects of industrialization, but in other countries people were aware of these evils earlier. Aimé Césaire, a French black poet, said over twenty-five years ago what so many young Americans are feeling today:

"Mercy, mercy for our naive and
 omniscient conquerors.
Hurray for those who never invented
 anything,
Hurray for those who never explored
 anything,
Hurray for those who never
 conquered anything,
  Hurray for joy,
  Hurray for love,
Hurray for the pain of incarnate
 tears."

I have to confess that I am excluded from the poet's blessing. I did once invent something. I have my name on the patent for a nuclear reactor which I helped to build over twenty years ago. The idea was to design a megawatt reactor which was so inherently safe that you could give it to a group of school children to play with and not worry about them hurting themselves. The reactor actually functioned well. The company I worked for sold fifty of them, which is not bad as the reactor business goes. A few years ago some people at Columbia University announced that they would buy one of these reactors and install it on campus for their nuclear engineering students. Immediately they were faced with massive protests from various indignant citizens of New York City. My name on the patent did not help. The citizens of New York City do not like to live that close to a reactor, even when it is certified harmless and foolproof by a theoretical physicist from Princeton.

In 1955, when the technology of nuclear reactors was suddenly declassified, scientists like me, who had had nothing to do with the earlier secret work in the bomb projects, were suddenly free to move in. We were invited to come and see if we could help make something peaceful and beneficent out of nuclear energy. That is how I came to partially invent a reactor. It looked like a golden opportunity to help mankind with science. Here was a brand-new, immensely powerful and world-wide source of energy. All we had to do was to make the production of nuclear energy cheap, safe, and abundant, and the age-old curse of poverty would vanish all over the earth. There was much talk of making deserts bloom and planting wheat over the arctic tundra. It seemed to us scientists at that time that the main problem with nuclear energy in the long run would be the problem of safety. We were not unaware of the shadow of fear that reactors trail behind them. We knew that a major accident in a major reactor would be a catastrophe, not only for thousands of people who might die miserably of radiation sickness but also for the future of the reactor business. So we decided as a matter of first priority to build a hundred-percent safe reactor. I think I have never experienced any greater feeling of satisfaction in any scientific work I have done than I felt in designing that reactor. The safe reactor was a technical success, and even a commercial success too. We felt proud that we had contributed substantially to the second industrial revolution, the nuclear-energy revolution. Clean, silent, safe and inconspicuous, the great power reactors would spread over the earth. With cheap electricity they would also spread prosperity and peace.



What went wrong with these visions? Why has the second industrial revolution not yet happened? Part of the answer is that twenty years or so is too short a time over which to judge a historical development of this magnitude. Reactors are spreading over the earth and are producing important effects whose shape cannot yet be clearly seen. However, even the most enthusiastic believer in reactors has to admit that the effects of nuclear energy have been less spectacular than we hoped. Briefly, the main reason we failed to produce the second industrial revolution is that we were defeated by the laws of economics. We succeeded rather well in making reactors clean and safe. We did not succeed in making them cheap. If they are not cheap they are of little use to a poor society.

So much for dreams. If nuclear energy cannot produce an industrial revolution, is there any other technological force that can do it? I believe there is and that we shall be faced during the next century with a technology which is truly revolutionary. By this I mean that, instead of stumbling against the laws of economics, it will change the rules by which economists think. Instead of stumbling against the laws of ecology, it will operate from the beginning in an ecological frame of reference. The new technology must grow out of an understanding and mastery of the basic processes of biology, just as our existing technology grew out of a mastery of the processes of chemistry and physics.

The idea that the second industrial revolution will be based on biology is not new. Wells and Haldane were saying this fifty years ago, and today our understanding of biological principles already goes far beyond anything that Wells and Haldane imagined. We are now in a position to speculate in some detail about the specific problems that a mastery of biological technology will bring with it. Our understanding of the human situation is grossly inadequate if it does not take such possibilities into account.

The word "scenario" is not the right one for the deliberately oversimplified sketches of future events that I shall describe. The right word is unfortunately familiar only to physicists, and it is "thought-experiment." The "thought-experiment" was invented by physicists as a device for clarifying their ideas. The purpose is to invent an imaginary situation in which the logical contradictions or absurdities inherent in some proposed theory are revealed as sharply as possible. As theories become more sophisticated, the thought-experiment becomes more and more useful as a tool for weeding out bad theories and for reaching a more profound understanding of good ones. When a thought-experiment shows that generally accepted ideas are logically self-contradictory, it is called a "paradox." A large part of the progress of physics during this century has resulted from the discovery of paradoxes and their use as a critique of theory. A thought-experiment is often more illuminating than a real experiment, besides being a great deal cheaper. The design of thought-experiments in physics has become a form of art in which Einstein was the supreme master.

The basic idea of my first thought-experiment was published in an article in *Scientific American* over twenty

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Professor Dyson, a theoretical physicist at the Institute for Advanced Study at Princeton, was a ΦBK Visiting Scholar in 1975.

years ago by the mathematician Edward Moore. It was called "Artificial Living Plants," but a more exact title would have been "Artificial Protozoa." Edward Moore is however not responsible for the use which I am making of his article in what follows. The thought-experiment begins with the launching of a peculiar-looking flat-bottomed boat from an inconspicuous shipyard belonging to the RUR Company on the north-west coast of Australia. RUR stands for "Rossum's Universal Robots," a company with a long and distinguished history. The boat moves slowly out to sea and out of sight. A month later, somewhere in the Indian Ocean, two boats appear where one was before. The original boat carried within itself a miniature factory with all the necessary equipment, plus a computer program which enables it to construct a complete replica of itself. The replica contains everything that was in the original boat, including the factory and a copy of the computer program. The construction materials are mainly carbon, oxygen, hydrogen and nitrogen, obtained from air and water, and converted into high-strength plastics by the energy of sunlight. Metallic parts are mainly constructed of magnesium which occurs in high abundance in seawater. Other elements which occur in low abundance are used more sparingly as required. It is easy to calculate that after one year there will be a thousand boats, after two years a million, after three years a billion, and so on. It is a population explosion running at a rate several hundred times faster than our own.

The RUR Company did not launch this boat with its expensive cargo just for fun. In addition to the automatic factory, each boat carries a large tank which it gradually fills with fresh water separated by solar energy from the sea. It is also prepared to use rainwater as a bonus when available. The RUR Company has established a number of pumping stations at convenient places around the coast of Australia, each equipped with a radio beacon. Any boat with a full cargo of fresh water is programmed to proceed to the nearest pumping-station, where it is quickly pumped dry and sent on its way. After three years, when the boats are dispersed over all the earth's oceans, the RUR Company invites all maritime cities in need of pure water to make use of its services. Up and down the coasts of California and Africa and Peru, pumping stations are built and royalties flow into the coffers of the RUR Company. Deserts begin to bloom — but I think we have heard that phrase before in connection with nuclear energy. Where is the catch this time?

Let us now analyze this thought-experiment carefully. It does contain, although in over-simplified form, a genuine paradox. The paradox lies in the fact that the RUR Company builds a finite piece of hardware which costs a finite amount of money, and seems to obtain in a few years an infinite pay-off. This result is in conflict with all the traditional rules of economics and social theory, which tell us that every increase in wealth has to be paid for at a stiff price. Of course the pay-off to the RUR Company is not really infinite, but the rate of growth of their capital investment is so enormous that it seems to contradict all the usual economic limitations. Human experience until now has taught us that a society can at best double its aggregate capital wealth in a period of decades or longer. The mastery of a biological technology which could double our capital in a month would mean that economics as it now exists would become meaningless.

Where is then the catch? There are two obvious snags in this thought-experiment. The first snag is the same one which we encountered in the nuclear energy problem. Artificial plants may provide us with a free supply of pure water, but it still costs money to use it. Just pumping fresh water onto a desert does not create a garden. In most of the desert areas of the world, even an abundance of fresh water will not rapidly produce wealth. To use the water one needs aqueducts, pumps, pipes, houses and farms, skilled farmers and engineers, all the commodities which will still grow with a doubling-time measured in decades rather than in months. The second and more basic snag of the RUR project is the ecological snag. The artificial plants have no natural predators. In the third year of its operation, the RUR Company is involved in lawsuits with several shipping companies whose traffic the RUR boats are impeding. In the fifth year, the RUR boats are spread thick over the surface of almost all the earth's oceans. In the sixth year, the coasts of every continent are piled high with wreckages of RUR boats destroyed in ocean storms or in collisions. By this time, it is clear to everybody that the RUR project is an ecological disaster, and further experiments with artificial plants are prohibited by international agreement. But fortunately, the prohibition does not extend to thought-experiments.

Let us then try another thought-experiment. The RUR Company has built a small self-reproducing automaton well-adapted to function in terrestrial deserts. It builds itself mainly out of silicon and aluminum which it can extract from ordinary rocks wherever it happens to be. It can extract from the driest desert air sufficient moisture for its internal needs. Its source of energy is again sunlight. Its output is electricity, which it produces with modest efficiency, together with transmission-lines to deliver the electricity wherever you happen to need it. The basic hardware components, the factory and the computer, are more or less the same in the rock-eating automaton as they were in the RUR boats. But the software, the computer program, is now enormously more sophisticated. The software of the RUR boat was like the DNA of a single-celled organism, a bacterium or an amoeba, which provides instructions to the organism only to produce an exact copy of itself. That is why I said the boat should have been called an "artificial protozoa" rather than an artificial living plant. When it is let loose in the ocean it does not know any better than to breed and multiply like a bug in a rotten apple. In contrast to this, the prototype rock-eating automaton is the fertilized egg-cell of a higher organism. The computer program of the rock-eater is like the DNA in a bird's egg. The program instructs the rock-eater to differentiate in a controlled way as it multiplies. It contains the blue-prints for building every one of its descendants, together with an elaborate switching system which ensures that descendants of many different kinds grow and function in a coordinated fashion. The fully developed colony of rock-eaters becomes as well integrated as the cells of a bird. There are automata with specialized functions corresponding to muscle, liver and nerve-cell. There are high-quality sense-organs, and a central battery of computer units performing the functions of a brain.

There is bitter debate in Congress over licensing the prototype rock-eater to proliferate over our Western states. The progeny of this one machine can easily produce a hundred times the present total power output of the

United States, but nobody can claim that it enhances the beauty of the desert landscape. In the end, the debate is won by the anti-pollution lobby. Both of the alternative sources of power, fossil fuels and nuclear energy, are by this time running into severe pollution problems. Quite apart from the chemical and radioactive pollution which they cause, new power-plants of both kinds are adding to the burden of waste heat which becomes increasingly destructive to the environment. Already by the year 2076 the Pacific coast from San Diego to Seattle is lined with power-stations at an average density of two per mile, to take advantage of the heat-absorbing capacity of the ocean. In contrast to all this, the rock-eating automaton generates no waste heat at all. It merely uses the energy which would otherwise heat the desert air and converts some of it into useful form. It also creates no smog and no radioactivity. Legislation is finally passed, authorizing the automaton to multiply, with the proviso that each machine shall retain a memory of the natural landscape at its site, and if for any reason the site is abandoned the machine is programmed to restore it to its original appearance.

Is it reasonable to postulate that a machine with such sophisticated capabilities for differentiation and specialization could reproduce itself in a time as short as a month? Of course, we do not know the answer to this question. We do not know even in principle the complete list of conceptual components which an automaton must contain in order to serve as the germ-cell for a higher organism. All we know is that higher organisms do grow from germ-cells in a remarkably short time. From a bird to an egg to a bird is a generation-time of a year, but this is the time it takes to reproduce a complete bird. From an egg to a bird is thirty or forty generations of cells so that the generation-time for individual cells of a higher organism is at most a few days. It seems that there is no inherent organizational limitation which would compel the generation-time of an artificial self-reproducing automaton to be as long as a month. The generation-time will probably be determined by physical rather than organizational factors. The thing will take time, using a modest input of energy, to process its raw material and fabricate all the parts necessary for its reproduction. The time will be shorter, the more closely its manufacturing processes can mimic biological rather than industrial patterns. I expect that the principles of embryonic development will be understood, both from the experimental and the theoretical side, during the next fifty years. When we have seen how Nature solved the problem of organization of the growth of a higher organism, we shall probably be able to adapt her methods to our purposes. I conclude that it is not absurd in the context of a thought-experiment to think of a month as the generation-time of even the most sophisticated automaton. This would mean that a world-wide system of machines could grow from a prototype egg-machine to full-scale operation within a few years.

My third thought-experiment is merely a generalized version of the second. After its success with the rock-eating automaton in the United States, the RUR Company places on the market an industrial development kit, designed for the needs of developing countries. For a small down payment, a country can buy an egg-machine which will mature within a few years into a complete system of basic industries together with the associated transportation and communication networks. The thing is custom-made to suit the specifications of the purchaser. The vendor's guarantee is conditional only on the purchaser excluding human population from the construction area during the period of growth of the system. After the system is complete, the purchaser is free to interfere with its operation or to modify it as he sees fit.

Another successful venture of the RUR Company is the urban-renewal kit. When a city finds itself in bad shape aesthetically or economically, it needs only to assemble a group of architects and town-planners to work out a design for its rebuilding. The urban-renewal kit will then be programmed to do the job for a fixed fee.

I do not pretend to know what the possibility of such rapid development of industries and reconstruction of cities will do to human values and institutions. On the negative side, the inhuman scale and speed of these operations will still further alienate the majority of the population from the minority which controls the machinery. Urban renewal will remain a hateful thing to people whose homes are displaced by it. On the positive side, the new technology will make most of our present-day economic problems disappear. The majority of the population will not need to concern themselves at all with the production and distribution of material goods. Most people will be glad to leave economic worries to the computer

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The Next Industrial Revolution

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technicians and will find more amusing ways to spend their time. Again on the positive side, the industrial development kit will rapidly abolish the distinction between developed and developing countries. We will then all alike be living in the post-industrial society.

The basis of the second industrial revolution will be a full understanding of biological processes and the imitation of these processes by means of computer technology. As we understand more about biology, we shall find the distinction between electronic and biological technology becoming increasingly blurred. It was John von Neumann, the mathematician, who first dreamed of this marriage between computers and biology. During World War II, von Neumann was working with great enthusiasm as a consultant to Los Alamos on the design of the atomic bomb. But even then, he understood that nuclear energy was not the main theme in man's future. In 1946, he happened to meet his old friend Gleb Wataghin who had spent the war years in Brazil. "Hello Johnny," said Wataghin, "I suppose you are not interested in mathematics any more. I hear you are now thinking about nothing but bombs." "That is quite wrong," said von Neumann, "I am thinking about something much more important than bombs. I am thinking about computers."

Von Neumann saw very early the profound importance in computer design of the separation between hardware and software, and he understood that this is exactly analogous in function to the separation between protein and DNA in living organisms. For a machine or an organism to reproduce itself, it is essential that it contain in symbolic form (as software or DNA) a complete description of itself, and in concrete form (hardware or protein) the machinery for translating the symbolic description into an actual copy. Von Neumann also understood that this separation of hardware and software was the key to the possibility of evolution of higher organisms. In evolving from simpler to more complex organisms you do not have to redesign the basic hardware (the biochemical machinery) at every step as you go along. You have only to modify and extend the software, the genetic instructions. Because of this indirect character of the evolutionary process, I am confident that when we have once mastered the art of constructing a practical self-reproducing automaton at the unicellular level, the extension of the technology to produce a complete system of automata coordinated like cells of a higher organism will not be far behind.

I have described what I consider to be the probable shape of the second industrial revolution. But there is nothing inevitable about it. If society decides that there is more evil than good in it, it can be stopped. Politicians can quite easily put a stop to technological developments, if they have the will to do so. But before a decision can be made whether these things are good or evil, one must know what the technical possibilities are and try to imagine as best one can the human consequences.

Haldane called the book which he wrote in 1924 about the future of science *Daedalus*. He imagined Daedalus, the mythological creator of the Minotaur, hybrid offspring of woman and bull, as the archetype of an experimental biologist. Daedalus is also pictured as the archetype of the deicide, the man who relentlessly destroys illusions and dethrones gods through his uncompromising assertion of scientific truth. Haldane ends his book by saying, "The scientific worker of the future will more and more resemble the lonely figure of Daedalus as he becomes conscious of his ghastly mission and proud of it.

"Black is his robe from top to toe,
His flesh is white and warm below,
All through his silent veins flow free
Hunger and thirst and venery,
But in his eyes a still small flame
Like the first cell from which he came
Burns round and luminous, as he
rides
Singing my song of deicides."

To those who knew von Neumann only through his outward appearance, rotund and smiling, to compare him with Haldane's Daedalus may seem ludicrously inappropriate. But those who knew him a little better, this man who so consciously set mankind moving along the road to the second industrial revolution, understand that from a psychological point of view Haldane's portrait of him was extraordinarily prophetic.

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