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Scientific progress. What can we expect?

The twentieth century was a marvellous century for science. There were four great landmarks in fundamental science:

Einstein's theory of special relativity in 1905, which shows that nothing can travel faster than light; that marked the end of classical physics;

Einstein's theory of general relativity in 1917 – really, it's a relativistic theory of gravitation – the force that holds the Universe together;

Quantum mechanics, which emerged between 1900 and 1925 as a result of successive discoveries by Max Planck, Niels Bohr, Arnold Sommerfeld, Wolfgang Pauli, Werner Heisenberg, Erwin Schrödinger, Max Born and Paul Dirac and an army of others. Quantum mechanics has become a set of rules, or laws, that descibe the motions of particles of matter no bigger than atoms and often a lot smaller. From it has flowed all present understanding of how matter is made from those particles.

The explanation of life, which is embodied in the structure of DNA established by James Watson and Francis Crick in 1953. That provides an understanding of inheritance in animals and plants as well as the reason why the cells of all living things function in the way required of them.

These four discoveries have radically changed our view of what the world is like. Relativity in both its versions means that we must regard the evolution of the Universe as a whole phenomenon, not something that happens to its individual components – the Earth, the Solar System, our Galaxy and so on. Quantum mechanics implies, as Dirac claimed in 1929, in the introduction to his great book *The Principles of Quantum Mechanics*, that "the whole of physics and chemistry has been reduced to applied mathematics". The discovery of the structure of DNA and its function in living things implies that life is a complex and intricate network of chemical processes.

I have said nothing so far about technology, but remember that Marconi first spanned the Atlantic with radio waves in 1903, that the Wright brothers first flew their measured mile in their home-made airplane at about the same time, and that all the electronic devices that now clutter our homes and desks could not have been designed before quantum mechanics was understood. I shall come later to the technology that has flown and will flow from the knowledge of the structure of DNA.

So, I contend, science has helped to make us healthier and wealthier than our grandparents could have imagined for us, and it has also made us wiser.

I have one warning at this stage: it's easy to form the impression that the twentieth century saw a succession of revolutions in science. That's not correct. Isaac Newton said in 1687 that "if I have seen farther than other men, it is because I have stood on the shoulders of giants". The giants of the past century whom I've mentioned have also stood on the shoulders of giants before them. Here are two examples: Galileo's discovery late in the sixteenth century that force and acceleration are indistinguishable was the cornerstone of Einstein's theory of gravitation more than three centuries later. And the late Richard Feynman, a natural genius of the twentieth century, based his own most important contribution to physics in 1948 on an argument due to W D Hamilton, an Irishman, in 1832. In science, the river of discovery has been unbroken for the past 500 years. So, I believe, it will remain.

But is not modern science too abstract to be meaningful for ordinary people, too strange to be taken seriously? That is a common complaint. Take the uncertainties linked with quantum mechanics for example. It's true that the positions and the speeds of electrons and atoms cannot be exactly measured or even specified, but so what? These objects are one millionth the size of the smallest things in the real world that we see with our eyes and from whose behaviour we have formed the intuitive impression that the position and the speed of objects can both be measured accurately. What reason is there to expect that microscopic particles such as electrons should behave like the macroscopic objects of the real world? Quantum mechanics is not a paradox, but a discovery about the nature of reality on the atomic scale. And quantum mechanics works. You could not design a computer chip without it. The uncertainties in the positions of individual electrons do not undermine predictions about the way in which pieces of semiconductor function.

My message is this: despite 500 years of continuous discovery, we remain ignorant of many important features of the world we live in. Science is nearer its beginning than its end.

1. WHAT WE DO NOT YET KNOW

Here is a checklist of our ignorance, each item of which will lead to new science.

We need a new vision of what space and time are like. The current crisis in fundamental physics is the conflict between Einstein's theory of gravitation and quantum mechanics. In my opinion, the crisis will be resolved only by attributing to space and time a microscopic structure of some kind. Only then shall we understand how the structure of matter and the large-scale structure of the Universe are linked.

We do not yet understand the origin of life on the surface of the Earth (let alone what life may be like on other plants), but there is no reason to abandon the view that the starting point was an abundance of inorganic chemicals on the surface of the Earth 4,000 million years ago.

Also, despite 150 years of dramatic progress, we do not understand the complexity of cells. Nor do we know how genes in cells are regulated. How, for example, do different kinds of cells, say white and red blood cells, emerge from common ancestor cells? We shall not know until molecular biology has become a quantitative science.

Then, too – despite great strides in genetics recently – neither the activity of particular genes within cells nor the causation of species differences is clearly undrstood. One result is that the balance between NATURE and NURTURE is incompletely understood. (I warn you against "genetic determinism" expressed by the legend "We are the products of our genes".) Another difficulty is that complex modes of inheritance (as in the major psychiatric diseases such as schizophrenia) can only be guessed at.

Although twentieth-century neuroscience has now provided a detailed picture of what nerve cells (neurons) are like and of how they function – which is a huge triumph – nobody yet knows how neurons are able to assemble themselves into a working brain. Nor does anybody know what happens when a brain thinks, or makes decisions. Even quite simple animals make decisions – they have "free will" – but the neural correlates of that function are unknown.

Despite concern in recent decades for the protection of the environment, too little for comfort is known of how to protect people against infections (such as AIDS, malaria and novel virulent strains of tuberculosis bacilli). And we are unable to protect ourselves against possibly cataclysmic meteoritic impacts – or even to predict them.

These questions will be a large part of the agenda of fundamental science for decades to come. The rest of the agenda will be driven by the questions we are not yet smart enough to ask.

2. WHERE THIS WILL LEAD

New technology will flow from all the items on this agenda. But there are a great many innovations waiting in the wings.

For example, computers will continue to get faster. Silicon-based computer machinery will probably improve by a further factor of 100 over 20 years. The true marriage of computer and communications technology will enlarge the use we make of these machines. Quantum computers exploiting the uncertainties of quantum mechanics promise still greater speed.

Computing machines (or their components) will be made by the self-assembly of synthetic molecules, by analogy with the ways in which nerve cells make connections with each other. When, and how, brain-like computers will be manufactured is a matter for conjecture. If the experience of the past few decades is any guide, we will probably be surprised how quickly these innovations will be on the market.

Remember, I'm talking about the innovations that will flow from present understanding. Now that there are techniques for the manipulation of single atoms, the synthesis of all possible molecules is on the cards. We shall have truly heat-resistant materials (up to, say, 3,000 K), chemical catalysts as specific as natural enzymes, sunlight-to-power conversion at ideal efficiency (by analogy with photosynthesis), truly high-temperature superconductivity (say 350 K). The application of jet-engine technology to power production reducing fossil fuel consumption (and CO_2 production) by between 30 and 50 per cent.

At some stage, supersonic aircraft will become commonplace and quieter for non-passengers.

Then there's biotechnology. Its economic impact so far has been small, but there is already a great deal waiting in the wings: better medicines, plants with built-in pesticides and so on. But public acceptance is bound to put a brake on the speed of development. That is why, in my opinion, it is ironical that those who insist that present generations owe a debt to the future are among the chief opponents of biotechnology, which is the only certain gift we have to pass on. Gene therapy, on the other hand, awaits the development of ways of placing genes where they really belong inside the cells affected by inherited diseases such as cystic fibrosis or haemophilia.

When we understand how the brain thinks, there will be a flood of technological applications not now foreseeable, but which will no doubt include the effective treatment of the major psychoses, the development of novel computational machinery and perhaps even of neurological manipulations for remedying the degenerative diseases of old age.

Nobody should be surprised that predicting technological innovation is more difficult than predicting advances in scientific understanding: the use made of inventions is determined by market and regulatory conditions.

A few general observations are nevertheless possible.

First, the last century’s technology ahs helped to make many of us healthier, wealthier and even wiser; we can reasonably expect that the future will have the same results.

Second, technological innovations, which themselves contribute to GNP (Gross National Product), also require that GNP should grow so that they should be affordable. You can make and sell cheap motor-cars only to a mass market that makes mass production economic. Regulatory regimes such as clean air legislation also contribute to GNP, but they also increase producers' costs. A corollary is, for example, that environmental protection, however it is financed, is a public purchase. Affording environmental protection thus requires extra increases of wealth.

Third, some but not all have been made wealthier by the innovations of the past century. The gap between rich and poor countries is a global problem in its own right. The ideal solution is a more global division of labour – a transfer of manufacturing enterprises to where they are not economic. Requirements that the poor countries should keep to regulatory standards rich countries believe they can afford (as the World Bank has begun to insist that developing countries should adopt rich countries' environmental standards) are counterproductive. Poor countries should be enabled to cut corners in their efforts to develop.

Fourth, the ethical debate will intensify. Science is ethically neutral, but technology is not. You may ask that scientists should pursue only "ethical" goals in research, but that is unrealistic. You cannot tell in advance what understanding of the world will prompt uncomfortable applications; nuclear fission sprang from academic investigations of the structure of the atomic nucleus, for example. Moreover, although science is a collective enterprise, all scientists would not even agree that all knowledge is beneficial. But the disagreement on ethical principles is widespread. Public opinions differ sharply even on the desirability of avoiding genetic disability and on the legalisation of abortion in the same context. The best that can be expected of science (which is not a guarantee) is that enough researchers will make it their responsibility to ensure that the world at large knows what is going on in laboratories.

There has been one striking illustration of how well that whistle-blowing can work. In 1975, a group of research scientists in the United States, alarmed at the malign potential of genetic manipulation, demanded a worldwide moratorium on research. They won their case, the moratorium lasted for eighteen months and most countries afterwards followed that with legislation.

Finally, the ethical problems thrown up by technology are unambiguously matters for governments, not science. In a global world, they are matters for governments acting in concert. The intergovernmental meetings called Gl7 would be better employed on questions like these than on the agendas that now occupy them.

FORESEEABLE PROBLEMS

I have given you what you may think is a cheerful view of what the future holds, but I do not pretend that the future will be trouble-free. On the contrary, some of the future's problems are with us already.

I've mentioned some of them. For example, there's the problem of resurgent infectious disease that has a simple biological origin. Micro-organisms (viruses, bacteria and the single-celled animals such as those that cause malaria) are now under greater pressure than ever because of the widespread use of antibiotics, as well as by the encroachment of human settlements on the natural habitats of animals such as the African monkeys that appear to have been the evolutionary origin of the AIDS virus. They, the micro-organisms, respond by evolving more virulent forms. Future generations will have to be more vigilant even than we are in defending people against infections.

I haven't mentioned global warming or the problem of climate change. I do not want to go into details, except to say that I believe the rate at which temperature will increase is overestimated by the computer models relied upon by the Intergovernmental Panel on Climate Change (IPPC). The exaggeration is probably by a factor of two. This may not sound much, but it could make a crucial difference to the planning of an appropriate response. Do not forget that environmental protection is a public purchase, and that money spent now on the conversion of power plants (and subsidising windmills) might be better spent on other public goods.

I have mentioned the danger of objects from space hitting the Earth. We should take this more seriously than we do. We know for a fact that an asteroid striking the Earth 65 million years ago was probably responsible for the disappearance of the dinosaurs. Many other impacts of that size are known to have occurred in, say, the past 1,000 million years. The most recent of them was in the South Pacific about 2.5 million years ago. Much smaller objects reach the Earth's surface much more frequently and can cause huge damage regionally: 10,000 square kilometres of Siberia were flattened by a meteorite in 1904. You will appreciate that this problem, like that of global warming, is one that affects the entire planet. But what defence can there be against cataclysmic impacts? The only suggestion so far is that asteroids approaching the Earth should be broken up by nuclear explosions. You will appreciate that such defences will not be easily deployed in a world in which nuclear weapons are tightly controlled by international treaties.

Implicit in my belief that we should take steps to avoid cataclysmic asteroid impacts is the assumption that the survival of the human race is desirable – that it should be a prime goal of global policy. That is probably a goal that most people would accept, but I suspect that none of us has thought it through. So let me give you an extreme illustration of the kinds of problem that might arise.

Human evolution occupies just 4.5 million years in the history of evolution, during which time there have been three distinct genera of hominids – the name for creatures on the way to *Homo sapiens*. They are the australopithecines, which were succeeded 2.1 million years ago by *Homo erectus* (who could stand up). Just when *Homo sapiens* proper emerged is uncertain, but there is evidence from genetics to suggest that it may have been as recently as 125,000 years ago. For most of this period, there have been two or more species of hominids alive at the same time.

Most of them have disappeared. The Neanderthals, apparently an offshoot of *Homo erectus*, vanished from Europe only 30,000 years ago. All this implies that human evolution has been very rapid and we shall never know where it might have led, for we have opted out of natural selection; we do not leave our offspring to their own devices, but offer them paediatric medicine instead.

It's also known that most of the species that have ever appeared in the fossil record have long since disappeared from it, not always (like the dinosaurs) because of some external impact on the Earth. Some, no doubt, lost out in evolutionary competition with better adapted species, but some may have gone because their genomes were unstable. So what will happen if a better knowledge of human genetics suggests that the human genome is fatally unstable? Apart from the speed of the process in the past 4.5 million years, there are some genetic diseases (Huntington's disease is one) where the underlying fault seems to be an error in the chemical mechanism for copying DNA.

It's crucial that if and when – and "when" must be several generations away, at least – we learn that Homo sapiens is doomed to extinction for some internal reason, there would be ample time to plan a response, many generations perhaps. But what would the response be? There would, I suspect, be general agreement among the human population that some kind of germ-line therapy for all individuals of reproductive age should be introduced as a matter of urgency. I suspect that many of the other goals we now take as sacrosanct, preserving biodiversity on the surface of the Earth for example, would take second place.

I do not believe this threat to our species is certain to arise, but merely raising the possibility highlights what is certain to be a live issue at some stage in the century ahead: EUGENICS, that is, the selective breeding of certain elements of the human race and the suppression of others.

The practice of genetic screening followed by abortion is a kind of passive eugenics, which will reduce (but can never eliminate) the frequency of deleterious genes in the human population. Geneticists routinely say that they will "never" manipulate the human germ line (the tissues that produce sperm and ova). For the time being, that promise is all very well. In their present state of ignorance, geneticists could not do it confidently and safely. But that will change, probably in the course of the century ahead. Whatever geneticists now say about the sanctity of the human germ line, I suspect their successors will find it prudent to be more flexible. So, in my opinion, they should be.

None of that means that we are on the road to eugenics as ordered by Hitler. What it does mean is that *Homo sapiens*, having opted out of the cruel disciplines of natural selection (which means tolerating a high death rate among children) is now forced to pay some attention to the fitness of the human genome for the tasks required of it. For we can no longer rely on Darwinian evolution to match the functions of our genes with the environment in which we find ourselves. Neither do we relish the prospect of being unable to adapt quickly enough to avoid extinction.

So there are problems ahead. But they are outweighed by the opportunities. My case is that the intellectual interest of the science that remains to be done is as great as it has ever been, and that the technology that will flow from it will further improve the lives of our species.

There are some people who hold that science has now matured in the sense that all the important discoveries have been made, and that what remains is to fill in the complex and often tedious details. That is false, as you have seen. So is the belief that a moratorium on discovery for the next century or so would help to simplify the handling of the ethical and social problems thrown up by technology. That is also false: many of the problems that face us can be solved only by learning more of what the world is like.

Science, therefore, is not at an end but more nearly at its beginning.