SCIENCE AS REVOLUTION (RTS/IET)

The title of my talk, Science as Revolution, is deliberately bold, because I want to persuade you that science is a highly revolutionary activity. When we think of revolutions, we usually consider major transformations only in the spheres of politics, economics, social organisation, or religion, and not of science. But to these I argue we should add the revolutions brought about by science, both cultural through improved knowledge of the natural world and of ourselves, and additionally through the major impacts that improved knowledge can have on the development of human civilisation. I think that science is the most long-lasting revolutionary activity known to humankind, because science generates systematic knowledge that stands the test of time. As a result science has long standing consequences for society, acting as a major driver of culture and civilisation, and of changes in the ways that we live.

So why is science such a reliable way of generating systematic knowledge of the natural world and of ourselves? It is because of the way that it is done. Science is based on a range of attributes and ways of working, not unique to science, but which are combined together in science in a very effective way. Science is based on reliable and reproducible observations and experiments which generate accurate descriptions of how the natural world behaves; such evidence forms the bedrock of science. From these observations and experiments, regularities and patterns can be recognised, which in turn lead to ideas and hypotheses to explain the workings of the world. Imagination and intuition are important in generating these scientific ideas and hypotheses, which are then tested by more observations and experiments.

This way of working has been emphasised by the philosopher of science Karl Popper. He argued that a scientist considers the data obtained by observations and experiments relevant to a natural phenomenon of interest, and then, through leaps of the imagination, develops a framework to consider that data, and to generate a hypothesis to explain the phenomenon. The hypothesis is tested further by using it to make new predictions, which are then examined by more experiments and observations. If the data do not support the hypothesis then it is either rejected or modified, and tested again. Sometimes it can be difficult to judge when a hypothesis should be rejected, because experimental or observational data are not always unambiguous and can be difficult to interpret. However, despite this difficulty, Popper's description does reasonably reflect the way that much of science works. An important implication of this view of science, is that scientific knowledge evolves, and is often tentative especially at the beginning of an investigation. It is only after repeated testing that it becomes more secure.

Science is also greatly influenced by the way scientists behave and interact with each other in a community. Good scientists are open, honest, rigorous in their thinking and in gathering accurate information, and be sceptical, especially of their own ideas. Francis Bacon, courtier, statesman and philosopher of the seventeenth century famously argued for a sceptical approach in the pursuit of knowledge, saying

"If a man will begin with certainties he shall end in doubts, but if he will be content to begin with doubts, he shall end in certainties."

However it would have perhaps been best if he had confined himself to thinking about science rather than doing science. Driving during winter in Highgate London he stopped his carriage bought a hen and then stuffed it with snow to see if it would delay putrefaction of the bird. As a consequence of his outdoor experiment he caught a chill, developed bronchitis, and died several days later.

An effective science community should also be interactive and collaborative, and encourage the constant challenge of data, ideas and hypotheses. However, although scientists work in a community they are also individualistic. Great advances are usually driven by creative and technically capable individuals. Parallels can be drawn with those working in the creative media, television for example, which also requires both collaborative team work and creative technically competent individuals. In both spheres of activity, good practitioners are often rather anarchic, and trying to organise or manage them is like herding cats.

The combination of these attributes and ways of working produces a methodology that underpins science, which is very effective at generating reliable knowledge of the natural world and ourselves. And this knowledge has led to revolutionary changes, both for our culture and beliefs as well as for the ways that we live.

Let me give some examples of these changes: until the sixteenth century the prevalent view was that the sun circled the earth. Copernicus proposed an alternative heliocentric view, that the earth and planets circled the sun, supported by Galileo's observational evidence obtained when he turned his simple telescope towards the planet Jupiter, and discovered the Medici moons circling the planet. Clearly not all celestial objects were orbiting the earth, lending strong observational support to the heliocentric views of Copernicus. Thus began a process whereby our terrestrial globe has become increasingly insignificant to just a speck in the universe. Our planet circles the sun which is a star that is only one of billions in our galaxy, and our galaxy is only one amongst the billions that make up the universe. And maybe there are even countless universes.

Another revolutionary change in our thinking came with Charles Darwin. He argued that living organisms have evolved and are related by descent, and he also postulated a major mechanism for evolution, natural selection. This demonstrated that the life sciences could be understood in terms of universal laws, just like the physical sciences, as Darwin himself recognised with the famous last sentence in the Origin of Species, referring back to Newton:

“whilst this planet has gone cycling on according to the fixed laws of gravity, form so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved.”

But most importantly and still contentious for some today, Darwin’s ideas moved human beings from being specially created to being related to the rest of the living world. Just as Copernicus had moved the earth from being the centre of the universe so Darwin moved humankind from a unique position separate from the rest of life.

Advances in science and the mind-set change of the Enlightenment, as Kant said "the emergence of man from his self-imposed infancy brought about the Industrial Revolution."

Science is very much a creature of the Enlightenment as indeed is this great Museum in which we sit tonight. The technological advances have been legion: The development of energy sources, steam, electric and internal combustion engines, nuclear and renewable sources of power; the use of new materials, iron, steel, ceramics, plastics, semi-conductors; of machines of manufacture leading to the robotised factory of today; of new means of transport, the rail locomotive, the steamship, the automobile, the aeroplane, the space ship; of advances in communication and the management of information with the telegraph, the radio, the television, the computer and the world-wide web. But unfortunately, together with these advances for the good of humankind, there have also been less desirable consequences: the construction of increasingly more effective and deadly weapons of war, and the over-development of industrialisation leading to pollution and damage to our environment.

Scientific approaches increased agricultural production such that crop yields today for each acre of land under cultivation are many times higher today than in the Neolithic times. Improvements in human health and increases in the longevity of humankind. Only one hundred years ago, even in developed countries such as the UK, life expectancy was around 50 years, probably only an increase of 15 years since the agricultural revolution 10,000 years previously. Yet in the last 100 years largely due to changes based on science, life expectancy has increased to around 80 years.

There has been other revolutionary consequences of science for society centred on the questions of what it means to be human. Like all other living organisms, human beings are to be understood in terms of their inherited genes, their cellular chemistry, and their interactions with the environment. So what does this mean for our sense of what we are, for free-will, for the use of punishment and justice, for equality? These are profound questions for society. Studies based on evolutionary genetics and animal behaviour have implications for ethics and morality. Science has a habit of invading other domains of human activity where at first sight it appears to have no place. This was the case for Galileo and Darwin, and is still the case today, with modern scientific advances having increasing impacts on spheres of activity, once thought to be the domains solely of philosophy, of politics and of religion.

Modern science has had another type of impact, also revolutionary, on human knowledge. Einstein in his theory of general relativity, proposed a continuum of space-time accounting for gravity, which undermined the common-sense view of the world expressed in terms of time and the three dimensions of space. Einstein's approach has resulted in a theory that is no longer completely in accord with our common-sense, that inherent to our framework of experience and understanding are time and the three dimensions of space. Studies of atomic structure led to Quantum Mechanics, an "Alice in Wonderland" world, a place where Schrödinger's cats can be alive and dead at the same time. But despite not being explicable in terms of a common-sense understanding of the natural world, the subsequently developed Standard Model has led to extraordinary precision in predictability of the behaviours of the ultimate constituents of matter. This is a revolutionary shift in human knowledge, where explanations can work beautifully, but are beyond our common-sense understanding.

Science leads to revolutionary advances in our knowledge of the natural world and ourselves, and this scientific knowledge results in sustained revolutionary changes to human society and culture. So how can we ensure that revolutions in scientific knowledge and understanding continue, and that they result in revolutionary improvements in the human condition?

Ensuring that excellent science continues to be carried out requires attention to how the research endeavour can be nurtured and sustained. Key to this is recognising that great scientific advances are usually driven by great scientists. We need to provide scientific education and training to allow such scientists to develop, then we need to identify and support them with an environment and adequate resources so that they can prosper. Most importantly, they need to be given the freedom to pursue what they judge to be interesting and they should be protected from counter-productive interference from often well-meaning but sometimes misguided scientific managers and leaders. Also I do not think that science ultimately flourishes in societies which are not free. Freedom of thought in science is essential and fundamentally that requires a free society. If we pay attention to keeping all of this in place, then science will continue to prosper.

Perhaps less clear is how to ensure that science continues to bring about improvements in the human condition. Critical for this is a good and healthy relationship between science and society. We need to make sure that science is used for the public good rather than the reverse. Science has always been employed for purposes that are not good for humanity such as for weapons of war which can even threaten our very existence, as is the case for nuclear weapons. Ultimately making good decisions about the use of knowledge based on science depends on societies with the right values, underpinned by healthy effective democracies. For science to play its proper role, requires a public at ease with science, and a democracy that can cope with the complex decisions involving science.

This needs to start in our schools. We have to provide a science education that not only trains future scientists for the next generation, always a very small fraction of total students, but also trains a future citizenship that can cope with the increasing effects that science will have on our democracy. Students need to be aware that science is a way of thinking, of experimenting and making observations, of weighing up of evidence. They need to know that science can be tentative in its conclusions, but can also lead to advances in knowledge of the world and of ourselves which can be relied on. Science is not simply a series of facts and figures, although some of these can be extraordinary, stimulating and inspirational; science is a process that builds reliable knowledge. Every student that leaves school should for example know the difference between astrology and astronomy, between the theories that underpin homeopathy and evidence based medicine. A key requirement of a modern educational system must be to equip a future citizenship to cope with the impacts that science and technology will have on their lives, and on the proper functioning of a healthy democracy.

The next challenge is how we can ensure that the public policy is made based on the best scientific knowledge that is available, and that the public is comfortable and supportive of those policies. Both Government and Parliamentary scrutiny procedures must be fully aware of how science can contribute to policy making, by ensuring they have access to the highest quality scientific advice and by heeding that advice. Scientific evidence and argument must be listened to and treated with respect. For this to be effective requires scientists to adhere to the highest standards of behaviour. They need to be open and honest, free from hype, to be absolutely clear about what knowledge is more certain and what is more tentative. This can be difficult when politicians and the public demand certainties that cannot be delivered. The other part of this challenge, ensuring the public is comfortable with the consequences of advancement in scientific knowledge, requires highly effective engagement mechanisms between society and scientists to be in place. Engagement is a two way process, and listening to the public concerns and their understanding of the relevant science is critical. Different fora and processes can deliver effective engagement, such as citizen juries, public consultations, opinion polls, and other mechanisms of grass root engagement. It is not adequate just to engage with lobby groups and single interest groups who may not always properly reflect the concerns of the public. Better engagement over complex scientific issues relevant to policy will bring about better policy, and help that policy to be introduced.

The other important issue is good communication about science in the mass media. Society as a whole needs to be well informed about advances in science, through the mass media of television, radio, newsprint, and the internet for example. There is a special need for the media, especially the media that reaches many millions such as television, to be highly responsible in their reporting. They need to avoid sensationalism, to be careful about so called balance when certain opinions have little evidential support or are potentially highly flawed, to avoid mystification and properly explain what can be difficult topics. There are excellent communicators of science in the mass media, and they should be given every encouragement as they do a great service in keeping science high on society's agenda and therefore high on the agenda of politicians as well.

There are threats to all of this. We need to be aware of those who mix up science, based on evidence and rationality, with politics and ideology, where opinion, rhetoric and tradition hold more sway. We need to be aware of political or ideological lobbyists who do not respect science, cherry picking data or argument, to support their pre-determined positions. We need to aware of those who distort science to support particular fundamentalist religious beliefs, not based on the rigour of rational argument and data, but on faith and revelation. We need to be aware of the relativists who argue that knowledge is culturally determined such that all views are acceptable, even those not supported by reliable evidence and rational reasoning. Revolutions are unsettling and are often strenuously opposed. This was the case with Copernicus moving the earth from the centre of the universe, and with Darwin who argued that man was not specially created. No doubt there were some who rejected the agricultural revolution of Neolithic times, just like some who reject the possible advantages of GM crops today, even when they can be for the public good.

At its best society has shown it can deal with these threats, I am optimistic that in the future society will increasingly see the value of science in bringing about revolutionary changes to our knowledge, and revolutionary improvements in society and the human condition. Science is truly the most long-lasting revolutionary activity known to humankind, and if it is nurtured and if the public are properly engaged, science will continue to bring great benefits to us all.