Predictability in Science: Accuracy and Limitations
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SOME ISSUES RELATING TO PREDICTABILITY AND CERTAINTY IN SCIENCE

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Science: The Triumph of the Reductionist Approach

We are aware that the human brain is gifted with an intrinsic sense of curiosity. It is because of this that human beings have wondered about their surroundings beyond the needs of survival. Nature around appears at first sight to be highly complex: in colour, form, sound, motion and the like – and therefore likely to pose serious difficulties for analysis and understanding. Human beings, however, have also been gifted with the ability to reduce this complexity to manageable proportions – through the power of logic and being able to look at the essentials that characterize any complex situation. It is, thus, that we have the apocryphal story relating to Newton and the falling apple, from which he deduced the far-ranging law relating to gravity. The great early scientific discoveries (like the Archimedes Principle, Newton's Laws of Motion, Galileo's experiments in Mechanics, and many such others) were all characterized by this effort to draw over-arching conclusions of a wide-ranging nature, by looking at the problem in its essentials.

Experiments are thus carried out on the essential parts of the phenomenon sought to be understood and observations made, with measurements of quantities; necessary methods and tools for the purpose are developed and constantly improved to increase precision. Often the latter lead to completely unexpected observations, uncovering new phenomena.

Lord Kelvin had remarked:

> When you can measure what you are speaking about, and express it in numbers, you know something about it. But when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of

knowledge, but you have scarcely, in your thoughts, advanced to the stage of science.

Efforts are also made to have large numbers of persons make the measurements and in many different ways; and to have a large number of measurements from which a statistical analysis can be made. It is only when there is agreement, amongst all of the data, that one feels confident or certain about the final outcome; and further, to ascribe a defined uncertainty to the measurement. An important part of any result thus obtained, is the error that can be ascribed to it, of a systematic or statistical nature.

Scientists have been able to make measurements of very different types over a range of fields such as astronomy, botany, chemistry, physics, zoology and the like. It was thus that the enormous wealth of nature could be separated into different categories; and within these, classified in appropriate ways which would enable discovery thereafter, of simple relationships that make it possible to make predictions.

Thus, Tycho Brahe devised new and accurate instruments like the quadrant and the sextant to make large scale astronomical measurements. From this, Johannes Kepler, after incredible and innumerable wrong guesses, gave up circles and ovals and tried the ellipse. Then, all of Brahe's work clicked into place. Kepler was able to generalize planetary motions. At this point, the laws only described the motions, but did not offer any explanations for their cause.

In a very different field, Mendeleev was able to take all the known available data concerning the various elements and classify them in a table in which there were a large number of gaps for new elements yet to be discovered but with broadly defined properties; this enabled prediction of new elements. This was the power of predictability based on meaningful classification.

Again, the famous collectors in the fields of botany and zoology, mounted expeditions to a variety of places in the world, to bring together great collections containing innumerable specimens and were able to classify these. Amongst the greatest of these was Charles Darwin, who was able to formulate the theory of evolution.

In parallel to this observational and experimental approach, there was the theoretical approach which was founded significantly in mathematics. Galileo, rightly regarded as founder of modern science, specifically referred to the use of mathematics in expressing experimental results. About the 'book of nature', he had remarked: 'It cannot be read until we have learnt the language and become familiar with the characters in which it is written. It is written in mathematical language'. As the concepts about the physical universe grew in complexity and subtlety, so did the mathematics to describe them. In the 18th and 19th centuries, there were gifted individuals such as Euler, Fourier, Gauss, Hamilton, Lagrange, Laplace and others who contributed to the development of physical sciences in the theoretical framework as also the mathematical underpinning of this. Later, when the quantum and relativity revolutions took place in the 20th century, the great mathematical edifice that had been developed independently purely within mathematics was made use (Poincare, Riemann, Minkowski and others).

It is this interplay between theory and experiment, underpinned by mathematics, that constitutes the essence of modern science. The extraordinary accuracies of predictions and observational verification of these made Dirac remark: 'This must be ascribed to some mathematical quality in nature – the quality, which a casual observer of nature would not suspect but which, nevertheless, plays an important role in nature's scheme of things'.

It is interesting to comment on the prediction and discovery of antimatter. The prediction was made by Dirac as a consequence of a purely theoretical approach representing the sheer power of intellect. The actual discovery of the existence of the positive electron was made by Anderson by adding a magnetic field to a cloud chamber and, thus, opening a new window through which he observed not only the positron, but also the particle of intermediate mass (between the electron and proton), now known as the muon. Again, the addition of counter control to the cloud chamber enabled Blackett and Occhiatini to demonstrate the creation of electron-positron pairs. Experimental discoveries of antimatter were, thus, entirely observational, and not as a result of a search for antimatter predicted by Dirac. In contrast, the search for the antiproton was planned with that objective.

It is possible to list out the very large number of cases of predictions based on mathematical and theoretical formulations as also through classification schemes (such as of Mendeleev and of elementary particles). One can also see the precision with which one can measure many physical entities such as the 'Lamb shift' or the 'g-2' of the electron and the muon (upto 0.6×10^{-9}) and, indeed of the precision with which one observes the black body microwave radiation characteristic of the Universe. All this illustrates the triumph of the reductionist approach in science.

Non-linear, Non-equilibrium Phenomena and Complexity

However, in spite of all this, and this is the edifice which has enabled science to be built up to where it is today, the real world is complex and I'll tell you a small story, relating to how I began to understand it that way.

Over 50 years ago, in 1951, I was sitting at a table in a canteen, in England, and I asked permission to sit because there was somebody else there. I never realized who that person was, though he happened to be one of the most famous persons I could have encountered then. We started talking and I was, of course, so full of what I was doing that I kept talking about it; until he asked me, 'Are you doing any teaching?', I said 'Yes, I've been asked to take a course in thermodynamics' and he asked me what I was teaching in thermodynamics. I explained the classical thermodynamics which one teaches at English undergraduate levels, concerning the first, second and third laws of thermodynamics, entropy and the like; and then he said, 'You know, young man, I think you have to realize that whilst all of what you are teaching is correct the real world is more complex than the standard laws of thermodynamics'. And then he gave me a little lecture for ten minutes on the whole area of complexity, non linear phenomena, and what now are referred to as dissipative systems. That person, whom I didn't recognize and know then at all, was Alan Turing. Alan Turing is a father figure in the field of computers, of automata, the Turing machine and so on; also famous for the work he did during the Second World War at Bletchley Park and the Enigma machine, breaking German military codes and the like. Unfortunately he committed suicide a little later. But the work that he was talking about, 'Turing bifurcations', and dissipative mechanisms, is what was referred to in later work of scientists like Prigogine. Turing had worked on these bifurcations in his classic paper of 1952 on morphogenesis.

What I want to say is that there is a great deal of what one would call simplicity, reductionism and direct predictability in science, but there is also the real world of complex systems which we encounter in real life, and that is what the public normally deals with.

The origin of this meeting goes back to some ideas proposed by the Academician Keilis Borok who had referred to similarities in a variety of complex systems and the underlying mathematics. He had given talks at the Academy on phenomena such as: earthquakes and seismicity; political, social and economic systems; patterns of crime; the behaviour of financial markets; traffic patterns; and the like. These are all highly complex situations which are also volatile in their behaviour. The question was how does science deal with such situations.

It has been pointed out at this meeting by Prof. Zichichi that there are different levels for understanding scientific phenomena. Thus, whilst we may make very detailed analysis of QCD, these relate to interactions involving quarks and gluons, but they do not come into the picture when we consider interactions between protons and neutrons. It is, thus, that one has the Newtonion-Galileian picture operating in normal mechanics but need an entirely new understanding through quantum mechanics when we go to the levels of atoms and electrons. One of the important questions to be considered is whether the complex phenomena encountered normally in society can be analyzed in reductionistic terms. Are there additional principles of nature that are superposed on complex systems which, of course, will follow all the other laws of nature that one has reduced through reductionist science? Is the whole greater than the sum of the parts?

In the earliest periods of human history, one has come across many examples of innovation and discoveries that have transformed human life and became the bedrock of civilization. These include 'the system of numbers', particularly 'the decimal place value system', and 'the zero'; 'the invention of the wheel'; 'the discovery of fire'; 'the selection of plants with economic value' and being able to grow them under controlled conditions; and the like. None of these developments are associated with the names of individuals. Since medieval times, and more particularly through the history of modern science, one has discoveries that are associated with individuals or schools of thought. But throughout this period, the discoveries remained largely within science and were of little concern to society. There are, no doubt, exceptions, particularly in relation to weapons of war which affected society. But, by and large, science was an internalized system.

Who will deny that the year 1666 was indeed The Year of Wonders (Annus Mirabilis) – for science. That was the year when Newton was responsible for spectacular scientific developments (Binomial Theorem, Fluxions/Differential Calculus, Theory of Colours; Integral Calculus/Inverse Fluxions; and Theory of Gravitation). All of these turned out to become the fundamental underpinnings of modern science. Yet none of these would ever be regarded by society then as being of importance to it. This was in contrast to the case of Galileo, who had just preceded Newton, who was an experimental scientist par excellence but was persecuted for his convictions which ran contrary to theological beliefs of that time. That, however, was a case involving those in authority and the hold they had on society at large. Similar to the case of Newton was that of Einstein who produced five spectacular papers that shook the foundations of physics in 1905. Yet these discoveries were of little concern to society at large.

This is in total contrast to the situation encountered today, where science cannot be regarded as so isolated. Scientific discoveries receive a great deal of publicity in the media (particularly the print media, radio and television). In addition, scientific discoveries very often lead to technological developments of a profound nature impacting on society.

With the development of technology through innovation, new artefacts continue to develop. Not all of these are of great use or desired by human society, at the time when they are developed. A large number would be acceptable because they represent improved versions of what was available earlier, or perform some new functions; for example, there are pharmaceutical products which have fewer side effects in terms of toxicity or are more effective or have a more desirable method of administration. There are other artefacts that are wholly new like: computers, TV sets, cell phones, internet and the world-wide web, genetic engineering and the like. These totally change the functioning and thought processes of society and are regarded as disruptive technologies.

It is these developments that often constitute the image of science in the public mind – an image of the extraordinary powers of the human mind to probe into the smallest and the largest, of living and non-living systems, to connect all of humanity, to imitate and mimic life-like processes, indeed leading to artificial life. With this image there is also, amongst many, a confidence in the invincibility of the technocratic fix and a certainty attributed to science.

Science and Social Problems

Cecil Powell, in an address that he gave in 1968 (Selected Papers of Cecil Frank Powell edited by Burhop, Lock and Menon, North Holland Publishing Company, 1972, p. 444), had remarked:

> Scientists ought also to play an increasing role in bringing their professional skills to bear on the grave public issues in which science is involved. They must not be seen as leading sequestered and comfortable lives indifferent to the great problems of the world and of their own countries, but as contributing some of their time and energy and expertise to their resolution. They are in a unique

> position to appreciate early the problems, the dangers and the advantages likely to follow from scientific developments and to make their findings known to governments and to peoples.

As has been clarified earlier, until the time of the Second World War, science essentially functioned at the fringes of society – the interactions were largely within the scientific community rather than with society. There were exceptions such as the role of scientists in the development of the chemical industry more than hundred years ago; as also in a variety of areas in which science has proved to be hugely beneficial for society such as the applications of X-Rays in medicine, the use of radio waves and broadcasting for communications, the development of chemotherapeutics and antibiotics which had a major impact on bringing down death rates and other such examples. It was, however, during the Second World War and, thereafter, that many aspects of science have come about that have large public implications, and which figure extensively in the audio-visual and print media.

The first of these was undoubtedly the development of the atomic bomb and the concept of weapons of mass destruction. This led to the famous Bertrand Russell – Albert Einstein manifesto and the creation of the Pugwash Movement. This was essentially a warning by scientists to society about the grave threats that such weapons posed. More specifically, scientists played a role in bringing to the notice of the governments the production of strontium 90 in nuclear explosions – and when these took place as atmospheric tests, that this isotope would be washed down and, being similar to calcium, find its way, through the food chain of plants and animals, into human bodies where it would produce radioactive damage. Whilst the atmospheric tests were important to the nation conducting them, this unintended side-effect would be global. This did have an impact; it led to a Treaty on Prohibition of Atmospheric Testing of Nuclear Weapons.

Since then, the number of grave issues faced by society has increased manifold. It would not be meaningful to list all of these. However, a few are indicated, where science has played an important role in bringing the issues to the notice of governments, and to the people of the world – demonstrating how prescient was Cecil Powell's remark in 1968.

There was the discovery of the ozone hole in the atmosphere by the scientists working in the Antarctica. This was essentially due to the use of ozone-damaging chloro-fluoro carbons and related chemicals by industry.

The destruction of the ozone layer (or a significant damage to it) would result in harmful ultra-violet radiation reaching the surface of the earth, where it can induce cancer. This was an event of grave societal consequence brought to the notice of governments by science. It also involves a straightforward technological fix: how to develop and introduce CFC substitutes into a global economy, which would do no damage to the ozone layer, and be economically acceptable. Through a series of intergovernmental meetings and treaties, efforts on this front have moved forward satisfactorily. Further, the ozone concentrations are also regularly monitored to keep track of new potential hazards.

Another area of long-term and grave concern to society is the increase in the concentration of carbon-dioxide and other greenhouse gases (particularly methane) in the atmosphere. At the time the Industrial Revolution had taken off, around 1780, with the development of the steam engine, CO_2 levels in the atmosphere were around 280 parts per million (ppm). They have reached over 380 ppm today with a slow rise at first and since then accelerating. If we adopt a Business As Usual (BAU) scenario, the levels could go up to 550 or even 700 ppm. Whilst we can measure the greenhouse gas concentrations with a degree of certainty, one cannot say the same about their future concentrations, pathways, sinks, and budgets at various stages. This involves an understanding of many aspects of the earth system, and their feedback interactions, particularly the inertia of the oceans, in acting as 'sinks' as also responding to temperature rise. An increase in greenhouse gas concentration would cause global warming. The Inter-governmental Panel on Climate Change, which won the Nobel Prize in 2007 for its sustained work over three decades in this area, has concluded that the warming would be in the range of 1.4-5.8 degrees Celsius. Whilst this may be small in relation to the range of temperatures encountered over the globe, it represents a global average warming with many impacts. It will be noticed that the warming has been indicated as being over a broad range and lacks the certainty associated with science. Further, as one proceeds to various impacts, such as melting of polar ice caps and of glaciers, change of surface reflectivity, extreme events in precipitation, sea level rise and the like, the uncertainties keep increasing. In such cases, the attitude in society and of many governments is that: if science is so uncertain about the magnitude of these impacts, why not wait till we know better. This is particularly so, since any measures to prevent such changes will involve behavioural change in society, with changes in lifestyle and increased costs. One is here dealing with non-linear processes that are potentially catastrophic. The potential impacts, therefore, need to be included in risk assessments. This is where there can be a prediction of the direction and possible magnitude of climate change but with considerable uncertainty concerning its details.

The subject of climate change is essentially the result of work of the Inter-governmental Panel on Climate Change and scientific work initiated, undertaken and managed particularly through the World Climate Research Program organized jointly by the World Meteorological Organization (WMO) and the International Council for Science (ICSU). It was a subject of major debate in the Second World Climate Conference held in Geneva in 1990, and became the basis for recommendations to the UN Conference on Environment and Development (UNCED), held in Rio in 1992. This resulted in the UN Framework on Climate Change, leading to the Kyoto Protocol and its targets in 1997. In spite of what science has done to forewarn Governments, the most recent report of IPCC is most worrisome.

The world scientific community has, therefore, fulfilled, in some sense, the role that Cecil Powell had indicated for it, in bringing to the notice of governments, and to peoples, some of these grave issues.

Another important subject that was brought to public notice by the scientific community at the Rio Conference in 1992, and prior to that, related to the loss of biological diversity. This has been a subject discussed in a variety of scientific meetings and, particularly, by large international non-governmental scientific organizations. The International Council for Science (ICSU) had, in the mid 1980s, initiated a program known as IGBP (International Geosphere Biosphere Program). This was essentially because it was felt by scientists that one could not discuss aspects relating to the geosphere (atmosphere, the cryosphere, oceans, climate change, and the like) without simultaneously taking note of the biosphere and the interactions that exist between these major domains.

We are aware that there is enormous diversity of other living matter (plant and animal kingdoms) with which we share our planet. Whilst we may have identified and named around one and half million, there are probably, in existence, anything from 3 to 15 million species. It is the insects and bacteria and less complex organisms concerning which we have very little knowledge. This bio-diversity, consisting of plants and animals, is vital for our existence; a few plants of economic value have been identified and form the basis for our food security today. A large part of our pharmaceuticals come from the plant kingdom.

And yet, as human beings multiply, and populations grow, the demand for land increases – for agriculture, plantations, industry, urbanisation, infrastructure and a variety of such purposes. There has been large scale unsustainable exploitation of forest areas, particularly from the viewpoint of the resources that they provide. This has been significantly aggravated by the nature of the consumer society that has been developing, which has been unmindful of the damage done to the eco-system. Scientists have, therefore, been deeply concerned about the loss of bio-diversity and its consequent implications. This was brought to the fore at the Rio Conference in 1992. It resulted in a convention in biodiversity; and also another on forest principles (which was non-binding).

There are many other issues with grave implications for society today, such as: the spread of new and emerging diseases, particularly with crossover infections from animal systems to people, the new opportunities being made available to society through stem cell work, genetic engineering, cloning, and the like, all of which have significant, long-term ethical implications. There are also broad areas of environment and ecology where society seldom looks at the price being paid for certain pathways of development that it has adopted. For example, what is the price to be paid to the ecological services provided by water. It is estimated to run into trillions of dollars and yet given no importance in discussions on development.

In all of these areas, we are dealing with non-linear systems, which can become, very rapidly, far-from-equilibrium systems. Whilst one can make certain predictions about the directions in which these developments can take place, it would be difficult to make unambiguous, clear-cut, predictions on where we will get to, and its consequences. Earth system science is in its infancy to be able to make exact predictions and, furthermore, to assert with any degree of certainty.

In the meantime, decisions have to be taken by governments and by society. For this, advice from the scientific community will be called for. This would involve the use of the precautionary principle in many cases to avoid getting into pathways that might lead to catastrophic events. But, it would also necessitate increased public understanding concerning predictability and how certain science can be. This is the role that scientists will have to play.