Predictability in Science: Accuracy and Limitations
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SCIENCE AS PREDICTION AND THE UNPREDICTABILITY OF SCIENCE

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This paper is about two different features of science. The difference is tied to two very different meanings of the same word, 'humanly', when a prediction is considered to be humanly impossible. One meaning relates to that most eminently human quality which is to act freely. And since such acts cannot be measured, they are not to be considered in reference to scientific predictions. Most cultivators of psychology would disagree, but they do so by changing the meaning of 'free' in reference to human acts. Yet unless they make that change freely, the change loses its meaning because it implies that all human minds, including those of psychologists, are acting like so many machines, blindly and inevitably. This facet was not noticed by William James, who a hundred years ago reported about psychologists (he was a chief among them) that they almost to a man held that new meaning of human freedom, which rendered the free will meaningless. The coming of Freudian and other forms of psychoanalysis did not shore up the case of human free will. Then in the 1930s there came a brief dallying among physicists with the idea that quantum mechanics allowed the free will to operate within a very narrow limit set by Heisenberg's uncertainty principle. Eddington, who first used that principle in that sense, took the view, and within one year, that the effort made no sense.

Another meaning of 'humanly' is purely pragmatic. There was a time when it was practically impossible for humans to predict lunar or solar eclipses. Ptolemaic astronomy removed that impossibility, but it did not thereby perform a prediction properly speaking. The Ptolemaic system of epicycles and eccentrics implied that there should follow eclipses at a given place and time in the sky. The prediction was so accurate that Copernicus' theory did not improve on it.

Until about a hundred years ago it did not seem possible to predict by science that the perihelion of Mercury might not be re-entrant. Although Newton spoke of that possibility, he also stated that a new physics was needed to predict it, but of that new form he had no inkling. Efforts to predict that advance by modifying the inverse square law, however slightly, led to impossible consequences in other respects. Strictly speaking even general relativity did not predict the advance of the perihelion of Mercury. The theory merely presented that advance as being implied in the essential parameters of the theory. It is another matter that what is implied in a theory is not immediately noticed by all physicists. Those who notice something which others have not yet noted deserve credit, but not for having predicted something that was strictly unpredictable, such as events contingent on free human actions.

Scientific predictions are better called extrapolations. Illustrations of this are all great advances of Newtonian physics, usually called predictions. They are just extrapolations, though with one difference. They are *exact* numerically. Examples are Euler's work on the libration of the moon, and Le Verrier's claim that another planet, still unknown in his time, causes the perturbations in the motion of Uranus. The claim had to include the determination of the spot and time where one was to look for a body which, once spotted, was named Neptune. The inability of classical physics to measure, which is an operation with numerically exact data or parameters, the influence of the ether on the earth's motion led to the abandoning of Newtonian physics. The latter implied exactly the opposite of what Michelson established with his interferometer. There is some exactness even in the so-called null result. The ability of Balmer's formula to indicate some spectral lines *exactly* led to Bohr's formulation of his atom model.

Exact science is 'predictive' though not in that strict sense in which, say a prophet, who is truly a prophet, predicts something. A true prophet has to deal with future events contingent on free human acts. A memorable example of this is Jesus' prediction of the destruction of Jerusalem and of the Temple. Humanly speaking it should not have happened, except for some human acts that are recorded in Josephus Flavius' *Jewish Wars*. I am not talking of the sloppiness of the guards of the Southern Gate, who left their post because of a torrential downpour in the middle of the night. This gave opportunity to a large number of ruffians to enter the City and reinforce there similar elements. Far more specifically human, that is strictly unpredictable, were some actions of John of Gischala, the general of Jewish forces in Galilee. After having been roundly

defeated by the Romans, he somehow escaped their grip, fled to Jerusalem where he told the leaders that he had just inflicted a crushing defeat on the Romans. This lie emboldened the defenders of the City to reject peace offers from Titus, who to the end wanted to save the Temple. He could not, however, prevent a soldier from throwing a burning piece of timber into the Temple, which then went up in flames.

In terms of a science that claims omniscience about all physical events, big or small, it may not have been absolutely impossible to predict that Peter would find a didrachma in the mouth of the first fish he would catch on Jesus' command. Even stranger things can be found in the mouths of fish. But if that ring had been thrown into the water by a free human act, then no science, however perfect, could have foretold Peter's success. So much for prophecy as distinct from mere prediction, which it is the business of science to make, though only of a specific form of science, exact science. Science is exact insofar as it relies on exact measurements, which are exact because they are operations with numbers.

Other so called sciences, such as political science, represent a very poor class by comparison. It was surely a poor prediction when Henry Kissinger predicted in 1988, two years before the collapse of the Soviet Union, that for the next hundred years the Soviets would remain the *other* superpower. Kissinger had been for years professor of political science at Harvard before serving as Secretary of State.

Exact science is predictive through the use of the only form of words, 'numbers', that imply a quantitative form of exactness, which represents a very special meaning of the word *exact*. Only of numbers is it not possible to state the phrase, 'more or less'. This point was made more than two thousand years ago in Aristotle's *Categories,* though he himself did not perceive how important a point he had made. He surely proved that human minds do not work like machines. Had he noted the importance of his remark, intellectual history might have become very different and exact physical science might have emerged two thousand years earlier than it did. Let it not be forgotten that Archimedes' method of computing the volume of a cone by approximation as if a cone were a set of slim disks all gradually smaller in diameter, came very close to the method of going to the limit which is the basis of infinitesimal calculus.

The ability of exact science to predict, that is, to unfold, should seem so obvious that it would be a waste of time to dwell on it. Quite different is the case with the other part of the title of this lecture, namely, the unpredictability of science. The unpredictability of science prior to the 17th cen-

tury was part of a presentation I gave nine years ago in this Academy, under the title, 'The Earth-Moon System and the Rise of Scientific Intelligence'. The paper dealt in part with the impossibility of predicting the accretion of a moon to the earth in such a way as to give the earth that very moon which orbits around it in the way it does. In spite of the great increase of the number of moons that have been for the last three decades spotted around other planets, the parameters of the earth-moon system remain unmatched. Yet the rise of Ptolemaic astronomy, which is the basis of all exact science, would not have been possible without that earth-moon system, or rather without the special lunar and solar eclipses it implies.

Further, there was the need for geniuses, such as Eratosthenes and Aristarchus of Samos. Their emergence on the Greek intellectual scene gives the lie to the Baconian method of doing science. That method implies that if one looks long and hard enough, one would find. This logic is no better than the saying that even a blind chick would find a grain now and then. In another form the Baconian method implies that the chances of finding are the greater the larger is the number of those who are looking. Well, the very large number of those who lent their computer time to make sure that messages from extraterrestrials would not be missed, left our isolation intact. No serious historian of Greek science ever claimed that the work of Aristarchus of Samos could be foreseen by earlier Greeks. No serious historian of Greek science ever suggested that three hundred years after Aristarchus of Samos, there would be a Ptolemy who would synthesize the work of earlier Greek astronomers. Different may be the case in reference to the rise of Euclidean geometry. Unfortunately we know only the names of the two hundred or so Greek geometers who had flourished before Euclid.

Some historians of science claimed that Buridan's epoch-making formulation of inertial motion in 1332 would have come anyhow. But such historians always showed a dislike for the epoch known as the Middle Ages, insofar as it was steeped in Christian, that is, Christ-centered faith. This faith, which was directly connected to Buridan's achievement, was not predictable, though it was prophesied. Nor was the coming of Buridan predictable. If the Black Plague, which claimed one-third of Paris, had come not in 1347 but twenty years earlier, Buridan might have died before obtaining the chair of natural philosophy at the Sorbonne. Kepler's three laws might never have become known to Newton, had Jeremiah Horrocks died not at the age of twenty-two but at the age of twenty. Young Newton might have died at the age of nineteen when he escaped from plague-stricken Cambridge to his father's farm. Then an apple might not have fallen on

his head to prompt him to think about gravitation. Neither the coming of geniuses, nor the fall of a given apple at a given place and time is predictable, if the context implies the free decision of one to take his seat under a given apple tree.

Once the three laws of motion were in place in Newton's *Principia*, the progress of science became a logical unfolding of the implications of those three laws. The steps of that unfolding, which had been taking place at an accelerated rate as time went on, was not something foreseeable in Newton's time. For decades the leading French geometers refused to accept Newton's *Principia* as a book on physics. No predictions could be made about the discoveries to be made in terms of Newton's physics, although some were increasingly looked for. Suffice it to recall the discovery that the mutual perturbation of planets cannot go beyond a maximum and that therefore the solar system was stable. This discovery, which Newton still claimed to be impossible to make, was done first by Lambert, and perhaps independently of him by Laplace. This detail would lead to the subject of simultaneous or multiple discoveries, a subject that would provide further doubts about the predictability of science.

No reputable historian of electromagnetism has claimed that following Weber, who among other things devised an electro-magnetic telegraph, Maxwell would formulate his electro-magnetic theory, although from Weber's work it followed that the speed of light was what was predicted by Maxwell's theory. Maxwell's theory, or rather his equations have not lost their lustre of originality and beauty. Einstein himself was so overawed by their perfection as to hold that they must retain their original form in all reference systems. Relativity theory has other motivations than purely scientific. Einstein himself did not realize early enough that his theory should have been called the theory of invariance. Even geniuses may fall short of their potentials, which is hardly a subject for predictions. Einstein himself admitted that special relativity would have been formulated even without him. The evidence of this is in Whittaker's *History of the Theories of the Ether and Electricity*. It is another matter whether one should give too much credit to Einstein's claim that the general theory needed him and him alone. It may very well be that Hermann Weyl would have formulated it, had Einstein not done it early enough.

No one who works in any branch of exact science can predict what happens there within the next fifty years except for some trivial points. A memorable registering of this came in 1950 when the editors of *Scientific American* asked eight prominent scientists to summarize the main advances

made within their respective fields during the first half of the twentieth century. About astronomy the Harvard astronomer Harlow Shapley wrote:

> Scarcely a question is asked of a doctoral candidate today [i.e. 1950] that would have made sense to the giants [of astronomy] of 1900. They would have been baffled, helpless and perhaps suspicious in the face of inquiries concerning photomultipliers, quantum theory, solar spicules, the carbon cycle, shell stars, the expanding universe, radio 'hot spots', the Schmidt reflector, Pluto, cosmic rays, and other common topics. Pride in our advances should be mellowed, by the contemplation of how much beyond us the astronomical world of 2000 A.D. is likely to be.

In 1950 no giant of astronomy would have predicted black holes, the 2.73°K cosmic background radiation, orbital telescopes, space probes, semiconductors, nanotechnology and so forth. Today nobody knows for sure whether in 2050 more than a few historians will remember string theories, let alone speculations about multiple and parallel universes. As for string theories, one cannot help admiring the wizardry of those who manipulated scores of dimensions in such a way as to lead to the mathematical formalisms underlying the four known physical forces, gravitational, electromagnetic, weak, and nuclear. String theorists have not claimed so far to predict the constants implied in those forces. As to cosmological theories that imply the change of the values of those constants with time, one can only predict a regular, but not a chaotic change. Predictions must obey the laws of logic. A chaos theory that implies absolute randomness is a contradiction in terms. Also the prediction cannot be random, let alone chaotically so. This would bring up the absolute priority of rationality over irrationality, of which more later. Inadmissible should seem the use of the term 'universe', which does not stand for a strict totality. Cosmological theories of multiple universes should seem suspect on purely logical grounds. At any rate, nothing specific has been so far predicted about any of those other universes.

To give a facetious touch to all such reflections by a historian of science on scientific predictability, I would like to recall that a hundred years ago Marcelin Berthelot, a notable French chemist in his day, but largely forgotten today, stated that around the year 2000 all human food would be in the form of pills. I am glad that the food service of the Vatican does not try to prove that prediction. Around 1900 Samuel Newcomb, the leading American astronomer at that time, claimed that machines heavier than the air could never fly. Fifty years later Vannevar Bush of MIT and presidential advisor on science, held that intercontinental ballistic missiles were impos-

sible to construct. Twelve years later two other presidential advisors, Wiener and Teller, gave two diametrically opposite views on space defense. President Kennedy quipped: 'I am therefore free to do whatever I want'. In 1959 Robert Leighton of Caltech and author of a highly regarded textbook on advanced physics, claimed that the study of fundamental particles had essentially been completed. He had no idea of the coming of giant accelerators, such as the one in Batavia, Illinois, or CERN in Geneva, built precisely to detect ever more elusive new particles of which it was well stated that none of them were really fundamental.

What alone can safely be predicted about the future form of physics is that it will become more and more complex mathematically. To say, as Roger Penrose did, that the future form of physics will be a new form of quantum mechanics which would include general relativity leaves intact the apparent irreducibility of summation and integration to one another. There is no middle ground between discontinuity and continuity. And as long as Gödel's incompleteness theorem remains valid, one can safely predict that a form of physics which would be necessarily true cannot be achieved. In other words, theoretical physics remains an open-ended venture. This conclusion was reached two years ago by Stephen Hawking after he had bemoaned half a year earlier the end of physics, because of Gödel's theorem. It means the end of only that form of physics which has on it the mark of hubris.

One can safely predict that Prof. Hawking will not see the realization of his prophecy, made in Beijing a few months ago, that he would be condemned by the Vatican in the same way as was Galileo. To begin with, the Vatican did not forbid Prof. Hawking to probe into the physics of nothing. John Paul II merely said that the creation out of nothing, insofar as that nothing is really nothing, cannot be handled by physics. Such is a most sensible statement, but beyond the common sense of some physicists, Guth for instance at MIT, who boldly speak about their power to create entire universes literally out of nothing. Once the talk of the town, but now largely forgotten, the steady state theorists claimed that their theory indicated the emergence of hydrogen atoms literally out of nothing. They did not like the comment of Pius XII on the theory as being gratuitous, although it could be viewed as plainly irrational. It is to the eternal credit of Benedict XVI that from the *aula magna* of the University of Regensburg, he reminded a Western world wallowing in all sorts of irrationalities – pragmatism, logical positivism, deconstructionism and the like – that rationality grounds all human discourse, whether about religion or anything else, including irrationality, whether science coated or any other kind.

Going from strictly exact forms of science to their partly exact forms, such as Darwinian theory, it is worth noting that it fails to predict future forms of species, let alone future genera and higher classes. This is all the more interesting because the scientific character of Darwin's theory lies in a fact, not fully recognized by Darwin himself. The fact is that there is a quantitatively measurable difference between parents and offspring, and that the impact of the physical environment, measurable in principle, must be different on the offspring and on the parent. Darwinian theory is science, but an exact science only in a very narrow and limited sense, a point which infuriates most Darwinists.

The inability of exact science to predict its own future, while it can predict far away events, in space and in time, is one of its serious shortcomings. About those shortcomings Polykarp Kusch, who received the Nobel Prize in 1955, said in 1963 that the power and impotence of physics are its two main sides and that both sides deserve equal scrutiny. He could have said that the future of mankind is as much in the hands of exact science as it is not. There is no scientific futurology. This is why the study of history is not a science though it can be a form of reasoned discourse. Rather unreasonable should seem long-range projections about physical situations, such as global temperature changes, that depend on an enormous variety of factors, some well known, some only guessed, and still others wholly unknown at a given moment.

Nothing can be predicted about another and very different kind of warming. It is the increasingly overheated availability of tools and gadgets delivered by science. It took a hundred years to put a billion telephones into human hands. It took only ten years, the last ten, to market another billion telephones. Similar figures, all indicative of an exponential rise, could be provided with reference to TV sets, automobiles, cameras and so forth. Libraries that have taken hundreds of years to develop now can be matched by electronic means within a few years. The text of all books printed in five hundred years may be available in five years if Google has its way. A single laptop can now house entire libraries.

It seems that the *génie* is out of the bottle and that nobody knows how to put it back there. Exactly seventy years ago when quantum mechanism was born, a strange proposal was made about that *génie*, although at that time nobody could foresee all that technological cornucopia which quantum mechanics would dump on mankind. In that year, we are in 1927, the British Association for the Advancement of Science held its annual meeting in Ripon, a quaint provincial town in Yorkshire. It was a custom that on

Sunday the Association would attend a church service, which in this case was led by the Anglican bishop there. He suggested that for three years all laboratories be closed so that scientists may have enough time to think over what they were doing. The next day it was the turn of Oliver Lodge, the grand old man of British science at that time, to speak at the banquet. He rejected the bishop's suggestion on the ground that it was impossible to halt discoveries. He was right, but I wonder whether he suspected that seventy years later scientific innovations would increase exponentially.

Science cannot do anything about this explosiveness. And I have not touched on what is being done in terms of genetics. Are we going to be duplicated, just because it is possible to do it? (Such was the argument on behalf of cloning of a member of President Bush's commission on the subject). This would not merely duplicate our problems, but make them grow hundredfold. Scientists cannot do much about a much simpler problem: namely, how to persuade science reporters to do their work responsibly.

In these times when so much is said about the interaction of exact science and the humanities, it is well to ponder a most human aspect of science. For the same reason that we humans cannot predict our own future, we cannot predict the future of our wonderfully exact science. This is so because it is a science made by humans who do not carry out everything exactly, not even their exact science. For better or for worse, scientists, as well as science, come with a built-in unpredictability.