Paths of Discovery
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THE ROLE OF INNOVATION, INTERDISCIPLINARITY AND PHENOMENOLOGY AS COMPONENTS OF CREATIVITY IN OPENING NEW WINDOWS

M.G.K. MENON

Introduction

Discovery involves the opening of a window to gain knowledge concerning the hitherto unknown. But the unknown, now being perceived through the discovery, already exists. This is an attribute fundamental to the concept of discovery. There are many ways in which discoveries are made. The aim of this particular meeting is to examine the multitudes of paths that lead to discovery, as also to look at some case studies based on personal experience.

In this paper, I wish to bring out the role that innovation, interdisciplinarity and phenomenology play in the process of discovery. There are many attributes associated with those who make discoveries: curiosity, originality, creativity, dedication and persistence, intelligence. The actual discovery may not be the direct result of a particular effort that is made, but would, in some sense, relate to it. The important words associated with the processes of discovery are: 'why'; 'what'; 'how'; – rather than 'who', which currently dominates society and media attention. Equally, it must be pointed out that just as 'why' is important so is, 'why not'.

Importance of a Questioning Environment for Discovery

Many of the older and static societies are dominated by dogma, by hierarchy and blind acceptance of authority. In this situation it is difficult for any individual to ask, on a free basis, any questions that would be in conflict with the existing situation. No doubt, in such societies, it is possible to ask all questions that do not in any way impinge on the existing order.

Concerning this, Gautama, the Buddha, had remarked:

> Believe nothing
> merely because you have been told it
> or because it is traditional
> or because you yourself have imagined it
> Do not believe what your teacher tells you,
> Merely out of respect for the teacher
> But whatever after due examination and analysis
> You find to be conducive to the good, the benefit,
> The welfare of all beings,
> That doctrine believe and cling to,
> And take it as your guide.

Role of Creativity

Another important element of discovery is creativity. This is manifest in many areas: science, engineering, architecture, art (painting, sculpture), performing arts, philosophy, religion, and many other such activities. Different parts of the brain are involved in the manifestation of creativity in these different areas. Creativity involves aspects that are different from pure intelligence. The latter is based on the faculty of thought and reason. Thus, through intelligence one may acquire and apply knowledge, and make extensions beyond existing knowledge, through the power of analytical reasoning. In the case of creativity, however, one deals with knowledge which has in it aspects of intuition, and generates new knowledge for which the building blocks are not the existing knowledge. One may use the same tools involved in analytical reasoning, or in areas of professional competence, but the result is something significantly related to imagination. Einstein remarked: 'Imagination is more important than knowledge'. While certainly there are many who are highly intelligent and also highly creative, one has many other instances of those not so intelligent, but who are highly creative. Apart from intelligence, which is undoubtedly a valuable asset for creativity, there are the very important attributes of dedication and commitment that are important for discovery.

Importance of an Interactive Environment

Concerning the role of an overall supportive environment and of team work, Jacques Monod commented in his Nobel Lecture on the importance to him of a Rockefeller Fellowship which gave him an opportunity to work at the California Institute of Technology in the laboratory of the Nobel Laureate Morgan:

> This was a revelation to me – a revelation of what a group of scientists could be like when engaged in creative activity, and sharing it in constant exchange of ideas, bold speculations and strong criticisms.

It is very clear that most human beings never stretch themselves to the limits of their abilities. It is the outstanding teacher who attracts the finest students; and, in the overall intellectual environment that the team represents, the individuals are pushed to the very limits of their intellectual capability, each deriving strength from the other in a resonant and supportive manner.

Illumination

New ideas often come to those who have been constantly thinking and struggling with a problem. This is beautifully illustrated by the great mathematician, Henri Poincare, who said:

> most striking at first is this appearance of sudden illumination, a manifest sign of long unconscious prior work. The role of this unconscious work in mathematical innovation appears to be incontestable.

Poincare gave a striking example:

> One evening, contrary to my custom, I drank black coffee and could not sleep. Ideas rose in crowds. I felt them collide until pairs interlocked so to speak, making a stable combination.

This related to Poincare's greatest discoveries, the theory of fuchsian groups and fuchsian functions, and arithmetic transformations of indefinite ternary quadratic forms.

Again, another great mathematician, Gauss, remarked:

> finally two days ago I succeeded, not on account of my painful efforts, but by the grace of God. Like a sudden flash of lightening the riddle happened to be solved.

Closer to home, in India, there was the mathematical genius Srinivasa Ramanujan. About him, the Cambridge mathematician, G.H. Hardy, remarked:

> In his favorite topics like 'Infinite Series and Continued Fractions' he had no equal in this century. His insight into the algebraic formulae, often (and unusually) brought about by considering innumerable examples, was truly amazing.

At the age of 16, he came across a book by George Carr which introduced him to the real world of mathematics. In this book only results were given, and proofs relegated to footnotes. Ramanujan proved the theorems by himself, often just as he got up in the morning. He claimed that the Goddess of Namakkal, (the goddess of learning) the family deity, had inspired him with the proofs in his dreams. He went through his short life, stating innumerable highly original and unconventional mathematical propositions in number theory, modular function theory and infinite theory on which mathematicians are still working; he did not provide any proofs. He went on to insist that none of these were his creation but revealed to him in dreams by the goddess.

According to many psychologists, creative thinking involves multiple stages: of preparation relating to the problem of interest and related aspects; incubation, whilst the mind is allowed to work on the problem in the subconscious; illumination which has been exemplified in the above examples of Poincare, Gauss and Ramanujan; and finally what is characteristic of the scientific method, the processes of analysis, validation and verification.

Invention, Creativity and Innovation

It has been pointed out already that discovery involves the process of perceiving that which already exists, whether it be a phenomenon or a law of nature. Children are discovering the world around them all the time; this is through their innate sense of curiosity, and the need for that knowledge for the daily processes of life and living. How and when that sense of curiosity dies down in most and changes take place in the cognitive processes needs further study. Information technology can provide a creative interactive environment, but an information overload may be quite negative.

However, when we talk of scientific discoveries, we imply that which has not been discovered before; and, therefore, truly constitutes a new window on nature.

In contrast, an invention involves the creation of something new – an artefact which has not existed before. This is a fundamental difference between discovery and invention. Because of the importance now attached to knowledge as a property right, inventions are very well defined in a legal sense, and protected by intellectual property rights.

Innovation is also defined as 'introducing something new'. It involves a process of change and of novelty; hopefully it should lead to successful exploitation of the new ideas. Innovation is often empirical, a result of tinkering, namely trying to do something in different ways, and from these efforts the best way would emerge. There is clearly intuition, creativity and intelligence, apart from originality, involved in innovation.

As different from scientific discoveries and inventions (that are largely in the area of artefacts and other aspects covered by intellectual property and copyrights law), innovation has a much broader connotation. Innovation may lead to a discovery or result in an invention. But innovation is much broader, extending over all aspects of human activity and at all levels, from the daily small opportunities to unique ones. Thus one talks today of innovation that relate to sectors such as management, marketing, human resources, law and much else. Very often, innovations that finally result in the application of an idea on a large scale, with an impact on society, has to take place across the full innovation chain, involving all or most of the facets just mentioned.

Internet was the result of an effort to achieve a specific objective: to network computer systems to achieve resilience in the case of a nuclear attack. This effort was initiated in the USA by DARPA (Advanced Research Projects Agency of the Department of Defence, USA). It involved MIT, Stanford University, Carnegie-Mellon University and others. When accomplished, it was taken over and used by a limited number of academic institutions. We know the pioneers who worked on it. It was not a sudden discovery; it was something that evolved. There is a humorous remark that it was the finest innovation ever made by a Committee! When the National Science Foundation took it over, and the Internet Protocol was developed, it became universal. And when the World Wide Web was developed at CERN by Tim Berners-Lee, Internet became what it is: an ever expanding horizon of global uses and users. The final outcome is the backbone of the IT revolution: the pioneering discovery of the transistor, and later the invention of the integrated circuit, have resulted in Nobel Prizes to those concerned. Otherwise, only components of this edifice, particularly areas of application, have been rewarded with intellectual property rights. But, overall, this was a grand innovation in the area of public good.

In 1992, one of the great industrial leaders of Japan, Akio Morita, Chairman, Sony Corporation, delivered the first United Kingdom Innovation Lecture at The Royal Society in London. The title of his lecture was: '"S" does not equal "T" and "T" does not equal "I"'. What he had to say was that scientific research provides us with information concerning that which was previously unknown; it provides new windows to look out at natural phenomena; and can result in great discoveries. But this, by itself, though it involves a high degree of creativity and originality, does not necessarily lead to applications or the development of technology. Technology is a process involving the manipulation of science and its discoveries to lead to concepts; processes and devices. He stated that technologists have a role to play not only in the development of technology, but also in leading high technology and manufacturing businesses. But he went on to say that technology alone is not innovation. Whilst there was need for creativity in evolving new technology e.g. involving new concepts, processes and devices, it was also necessary to have associated creativity in product planning and creativity in marketing, to enable the new technology to fructify. He further emphasized the importance of innovation in management, and the importance of an innovation mandate which has to be defined by business as well as by government. Morita was referring to innovation in the context of the totality of the 'innovation chain' which has to be effective for successful or commercialization and large scale application to take place.

In a personal discussion he argued why the pocket (transistor) radio was not a great discovery or technological invention, but was an important innovation. The valve radio was known and in use. The transistor had been discovered; thereafter the integrated circuit had been invented. When these were used to replace the valve, the circuits became smaller and lighter, with less demand on power. Small dry cells could be used. The loudspeaker had to be miniaturized and the whole entity packaged and marketed. There were a large number of innovations which added up to make a huge commercial success.

INTERDISCIPLINARITY

In the early days of scientific development, science was regarded as natural philosophy – and that designation still persists in some educational institutions. That was when science concerned itself purely with theoretical and philosophical questions. This changed when the experimental method became part of science. Even at that stage, with the limited number of extraordinary individuals engaged in the scientific endeavour, whose names have come down to us – the rest being purely technical practitioners – their coverage was wide, Thus a Galileo or Newton covered areas of mechanics, optics, gravitation, astronomy and mathematics. A Faraday would deal with electricity, magnetism, chemistry and the like. Where can there be another Leonardo da Vinci who spanned science, engineering and creative arts at his level? More individuals could be cited; and even at other levels, they were truly natural philosophers. With the passage of time, this has changed. Many great names were associated with narrower fields in which major advances took place. Then, as understanding increased, fields started to come together. One of the characteristics of modern science has been the process of bringing fields together, through a broader understanding of common principles. Thus, all forms of energy began to be understood in a unified frame work: the law of conservation of energy and thermodynamics were born. Electricity and magnetism converged within the framework of electromagnetism (em). Electrodynamics developed. The em and weak forces were seen to be components of an electroweak interaction, and then chromodynamics which unified all of the strong interactions. From what is the 'standard model', one is looking for a 'theory of everything'. Under the rubric of the periodic table, all of the elements that constitute chemistry came together. With atomic theory and the chemical bond there arose an understanding of chemical reactions. Electrical energy was the first of the wholly science-based technologies. Now chemistry and chemical engineering have also changed from being empirical areas to being wholly science-based.

In general, there is a move towards convergence in technologies, (the most striking being in information technology and biotechnology), and of unification in science. This has, and will continue to offer opportunities for cross-over of ideas and techniques from one field to the other. Even more, such crossovers can take place, with revolutionary consequences, between highly disparate fields.

To take one area at the frontiers of modern science – that of the brain and neurosciences. This is a field where classical neurosciences (neurology, neurosurgery, psychiatry etc.) intersect now with molecular and cellular biology, biochemistry, cognition and sensory perception, education, psychology, imaging techniques, mathematics, computer sciences and artificial intelligence, engineering and so on. This is getting to be truly inter disciplinary – perhaps a fairly unique example.

Whilst discoveries will continue to be made in specific narrow disciplines, it is at the newly developing interfaces of the various disciplines that the greatest opportunities lie.

PHENOMENOLOGY

Nature is studied, first and foremost, by observations relating to the various ways in which it manifests itself; phenomena are those that are perceived by the senses and augmented by devices that enhance the power of the senses. The scientific study of phenomena is referred to as 'phenomenology'. Many of the great discoveries in science have come about through phenomenological studies.

Many in society regard these discoveries as accidental, or attribute them to serendipity namely, making discoveries of things that one is not in quest of, by accident and sagacity. There are many instances that one can give in this regard: for example, the discovery by Henri Becquerel of photographic material that had blackened sitting in a drawer – which opened up a whole new field of radioactivity, leading to nuclear physics and all that followed; or the discovery, by Alexander Fleming, of penicillin in an open glass dish, which opened up the whole field of antibiotics. These events are not accidents in the standard sense of that term. The discoverers were individuals with a sense of curiosity, sagacity, originality and, later, dedication and commitment to pursue the lead, so necessary for any such discovery to be meaningful.

I would like to recount what Karl Popper had said in this connection:

> Suppose that someone wished to give his whole life to Science. Suppose that he therefore sat down, pencil in hand, and for the next twenty, thirty, forty years recorded in notebook after notebook everything that he could observe. He may be supposed to leave out nothing: today's humidity, the racing results, the level of cosmic radiation, the stock market prices and the look of Mars, all would be there. He would have compiled the most careful record of nature that has ever been made; and, dying in the calm certainty of a life well spent, he would of course leave his notebooks to the Royal Society. Would the Royal Society thank him for the treasure of a lifetime of observation? It would not. The Royal Society would treat his notebooks exactly as the English bishops have treated Joanna Southcott's box. It would refuse to open them at all, because it would know, without looking, that the notebooks contain only a jumble of disorderly and meaningless items.

The reason is that as Paul Weiss has said: 'The primary aim of research must not just be more facts and more facts, but more facts of strategic value'.

It is interesting that Albert Einstein had once remarked that one of the great gifts that he had was a good nose e.g. know what to look for, identify the essentials and see the importance and relevance of an approach.

Phenomenological Studies of the Cosmic Radiation

I refer in this paper to the phenomenological approach, because the field in which I worked was that of cosmic radiation, which provides a very good example concerning the power of phenomenological methods, as well as of the interdisciplinary approach in making discoveries. I started my research career in this field at the University of Bristol in England in 1949 working with Prof. C.F. Powell.

In the Nobel lecture that Prof. Powell gave in 1950, he spoke about the discoveries that studies in this field had led to. In particular, he gave an interesting quotation from the 1928 edition of the 'Conduction of Electricity in Gases', by J.J. Thomson and G.P. Thomson:

> It would be one of the romances of science if these obscure and prosaic minute leakages of electricity from well-insulated bodies should be the means by which the most fundamental problems in the evolution of the cosmos came to be investigated.

As time has gone on, this has increasingly proved to be the case.

It was in 1785 that Henry Coulomb noted that a metal sphere that was suspended by an insulator thread invariably lost the charge placed on it; this was more than what could be attributed to the loss of charge through the thread itself. Later, gold leaf electroscopes seemed to lose their charge at sea level, even though they were well-insulated electrically. C.T.R. Wilson, who invented the cloud chamber and was awarded a Nobel Prize for this work, connected this phenomenon with ionization of the surrounding air. This could have been due to radiation at ground level; this appeared possible after the discovery of radioactivity by Becquerel. There were unsuccessful efforts to reduce this by shielding the electroscopes. To explore this phenomenon further, in 1912, the Austrian scientist Victor Hess, flew instruments on balloons which he piloted himself. He observed that the phenomenon increased rapidly up to the highest altitude of around 6 kilometers attained by the balloons; and further, remained the same during the day and at night. He concluded that this was due to the incidence of a highly penetrating ionizing radiation from outside the earth, but not from the sun. Later this radiation was given its present name of cosmic radiation by Millikan.

Ever since this initial discovery, scientists studying cosmic radiation have significantly followed a phenomenological approach. They have studied the various components of the radiation, in terms of their nature as well as intensity, and variations of these as function of height in the atmosphere, depth below ground, across latitudes, in relation to events on the Sun etc; and garnered a remarkable amount of information.

We now know that cosmic radiation is like a very thin rain of particles impinging on top of the earth's atmosphere. They consist of neutrinos, electrons and protons, and charged nuclei of elements from helium up to uranium. Protons constitute the most abundant component. Their energies range over 15 orders of magnitude, up to energies far greater than any accelerator can, or is conceived to, produce on earth. Being charged particles, they are subject to the influence of magnetic fields. The earth's magnetic field, whilst enabling all the lower energy particles to pour in at the poles, prevents radiations with energies below a geo-magnetic cut-off coming in at other latitudes, with the highest cut-off being at the equator. The low energy component is also subject to variations caused by electro-magnetic conditions in the earth-sun vicinity. These radiations, in passing through the earth's atmosphere, collide with the air nuclei; and in these collisions are born new short-lived nuclear entities. In addition, there is a total breakdown of the heavy nuclei into their component fragments; as also the generation of showers and cascades.

The study of cosmic radiation gave birth to a whole new field of elementary particle physics, including discoveries relating to transient nuclear entities that live for very short time periods. The major discoveries in this field were of the mysterious muon and verification of the existence of the positron, the first example of antimatter that was theoretically predicted by Dirac. This was by Carl Anderson using a cloud chamber equipped with a magnetic field. The phenomenon was observed and then interpreted. They were not looked for, in the sense of conducting an experiment to verify the prediction of a theory. Then followed the observation (discovery) of electron positron pairs, as predicted by Dirac. Apart from these discoveries, after the Second World War, a whole new world of subatomic particles was discovered. These included the charged and neutral pions, and their decays, strange particles (concerning whose discoveries and modes of decay I had worked), excited states of the nucleon etc. These discoveries were made using nuclear emulsion techniques and cloud chambers. These discoveries gave an impetus to the building of larger and larger accelerators for elementary particle investigations. The field was dominated by cosmic ray observations for two decades, from the mid-thirties to the mid-fifties; it was then taken over by the accelerators. But the very high energy cosmic ray interactions, including those that produce the giant air showers, continue to remain the domain of cosmic ray observations.

In the preceding paragraphs it will be noted that I have also indicated the detector systems that were used for making the various discoveries. These detector systems did not exist in nature. The development of these, therefore, was not really a discovery, but an invention. But these inventions resulted in discoveries. And invariably, when a new technique was brought into play, nature yielded up some of its secrets.

Prior to the discovery of the cosmic ray window into the Universe, one only had the electro-magnetic window. This covered a narrow optical wavelength interval. All that we knew about the Universe then was due to the photons of visible light. Observations through this window were greatly enhanced through the invention of the spyglass or telescope by Galileo. In the mid-thirties, the discovery of radio waves from objects and regions in the Universe greatly expanded the electromagnetic window. Today, there are giant telescopes operating across a wide spectrum of photon wavelengths: from the radio waves, the infrared, visible, ultraviolet and X-ray bands; different types of information flow through these windows.

We are aware that there is a major force of gravitation that pervades the Universe and one would hope to be able to detect gravitational radiation – but this is yet to be observed. One became aware of phenomena that would give rise to neutrinos from space, but because of their extremely small cross-section for interaction, difficulties in observing them were anticipated. Only recently have the clear signals of neutrinos from the sun, as well as of galactic neutrinos been detected – these have called for the invention of the giant detector systems.

The particle radiation from the Universe, including the neutrinos, that the cosmic radiation represents is unique in many ways. The charged particles are subject to electromagnetic fields; their acceleration to the extraordinarily high energies seen is also the result of electromagnetic fields. They interact strongly with matter, this causes changes in their composition. The neutrinos come direct from the source, since they interact so weakly and are not subject to electromagnetic fields. What we can gather about the Universe from the particle radiation is, thus, very different from that derived from the electromagnetic radiation.

The field of cosmic radiation has thus provided windows into the Universe that were not otherwise available. In most cases, discoveries made in the field of cosmic radiation were not expected nor planned for. They were entirely observational in nature and, therefore, passive experimentation. The discoveries were, thus, of a phenomenological nature, aided by inventions of systems for better observation of the phenomena.

Often, the new detectors were invented and because of that new phenomena observed.

The field has also been one that represented interdisciplinarity – on the one hand relating to nuclear elementary particle physics and, on the other hand, to astrophysics and cosmology. And, today, in our efforts to understand the Universe, the very small and the very large are coming close together. All this started with the initial observation of the leakage of electricity from well-insulated bodies.

Deep Underground Cosmic Ray Experiments – A Personal Account

I would like to recount one example of a phenomenological approach with which I was closely associated, that opened up an entire new field. As mentioned earlier, cosmic ray physicists had made efforts to observe the radiation from a variety of aspects: in terms of its composition, energies, phenomena that they gave rise to, variation with altitude, latitude and depth. With regard to the last, namely, the depth variation of cosmic rays below ground, we had a group working at the Tata Institute of Fundamental Research, Bombay. It had initially measured how cosmic ray intensity changes as one goes below ground – in railway tunnels or shallow mines where there is some overburden of earth. However, in India, in the Kolar Gold fields, depths up to 2 miles below the earth's surface are available. An experiment was, therefore, mounted to establish the depth-intensity curve up to the greatest feasible depth. When the detectors (Geiger-Muller Counter Telescopes, 3 square meters in area) were taken to the greatest depth of 9,600 feet below ground, no counts were observed in a period of 60 days. This clearly indicated that the intensity of the atmospheric muon component had been attenuated to a very significant extent. We then calculated what might be expected from neutrinos produced in the atmosphere, traversing the earth, and interacting to produce muons in the rock surrounding the detector. For neutrinos in the GeV energy range, it appeared that the number of events of neutrino-induced muons passing through the detector would be adequate for observation. We immediately mounted an experiment with a suitable neutrino telescope; and were the first to observe the interaction of atmospheric neutrinos.

A similar experiment was done, somewhat around the same time, by Fred Reines and his collaborators in the South African ERPM Gold Mines. Reines was later awarded a Nobel Prize for his work on neutrinos, particularly the first observation of low energy reactor neutrinos along with his collaborator, Clyde Cowan; until this discovery, the neutrino was essentially a theoretical artefact created by Pauli. A major experiment on low energy neutrinos originating from the Sun was carried out by Ray Davis which earned him a Nobel Prize.

It is all of this work, starting in the mid 1960s which has given birth to the field of neutrino astrophysics. Many Russian and Japanese scientists have contributed to ideas and experiments in this field.

We have seen in this part of the paper, how observations carefully made of phenomena, have led to the opening up of wholly new fields: radioactivity and nuclear physics, antibiotics, and cosmic rays (the story of which has been described in some detail). Many similar examples can be alluded to.

One may well ask what is the future of such an approach for making discoveries. One has seen in one case almost a repeat of the phenomenological approach in the same field. Karl Jansky opened up the field of radioastronomy, and decades later Penzias and Wilson discovered cosmic microwave background radiation; in both the cases these constituted careful observations relating to radio signals from space. Astronomy and astrophysics, in particular, is full of fairy tale stories of discoveries such as pulsars, black holes, dark matter and so on.

It is clear that the phenomenological approach will continue to pay rich dividends. Perhaps only the scale of the effort and the nature of detector systems will perhaps undergo major changes. But as long as one is dealing with individuals with a sense of curiosity, who can discern the important from the unimportant, and have a good nose as Einstein remarked, discoveries will continue to be made.

Conclusion

One has seen extraordinary minds over the past few hundred years, such as Darwin, Faraday, Galileo, Gauss, Newton, Pasteur, Leonardo da Vinci; and over the last century, Bohr, Crick and Watson, the Curies, Dirac, Edison, Einstein, Fermi, Pauling, Poincare, Rutherford, Thomson, and many more. The windows they opened, and the profound understanding of nature that their original thinking led to, has undoubtedly been the base for so much that has followed in the areas of application with a succession of rapid and great innovations. The pioneers of nuclear energy and of the space programmes, of flight and the jet engine, of computer science and information technology, of molecular biology and biotechnology, of the many areas of chemistry and new materials, and of the underpinning mathematical sciences, are all too numerous to be named; comparisons are always difficult; and yet each one of these represents wholly new areas of human progress. Any one of these could have been picked up, to describe in greater detail, aspects relating to discovery, creativity and innovation.

What is important is that there was a fertile soil in society which could lead to the flowering of these extraordinary minds and the areas that they launched. This is the civilizational and cultural framework of a scientific society. But for it to be truly in the public good, it must be complemented by creativity in the many other domains which ultimately make a complete human being and define values needed for human happiness.

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