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GUEST EDITORIAL

Some reflections on science and discovery

Observations, ideas, and discoveries are the substance of science. We are, in a very real sense, creatures of the mind, building science on the tenuous fabric of human thought so that it becomes its own evolving tapestry, a tapestry that must be passed down from generation to generation without unravelling.

Only a few months after receiving my Ph D in nuclear chemistry in 1974, I presented a seminar at the University of California, San Diego. There were two men in the audience whom I only knew by reputation: Nobel laureate Harold C. Urey (1893–1981), who discovered deuterium and conceived the idea of oxygen isotope paleothermometry, and Hans E. Suess (1909–1993), co-discoverer of the shell structure of the atomic nucleus, which earned co-discoverer J. Hans D. Jensen a share of the Nobel Prize in physics in 1963. Both Urey and Suess were recipients of knowledge passed down from masters. Urey had served a postdoctoral apprenticeship with Niels Bohr in Copenhagen; Suess had learned from his father Franz Eduard Suess, a famous geologist, who had learned from his father, Eduard Suess, an even more famous geologist and author of *Das Antlitz der Erde* (1892). Something I said during that seminar led to my being invited by these two giants of science to serve as a postdoctoral apprentice to them.

Suess and Urey were well schooled in the principles, methods, and ethics of pre-World War II science, a time when science received little government funding. After the war came the Cold War and government became the primary funding source for most scientific research. The US National Science Foundation was established in 1951 and wrote the new rules for the government administration of scientific research funding, including anonymous peer review. Secret reviews by one's competitors encourage deceit, human nature and the logic of competition for limited resources being what they are. Further, the requirements for funding proposals trivialize science by insinuating non-scientific or political ends into the process of rationalization. How can one specify beforehand what will be discovered that has never before been discovered, or what one will do to make that discovery? By 1974, the tapestry of science was already frayed. Now, 41 years later, I wish to pass along some of the insights I learned from Urey and Suess, as well as during my own life of making scientific discoveries.

The purpose of science is to determine the true nature of the Universe and all it contains. The word 'true' is paramount. Science is about truth and integrity. But in many other human activities, politics for example, truth does not have the same necessity as it does in science. (Although as acknowledged by Mahatma Gandhi, 'Truth never damages a cause that is just'.)

Science is the ever-evolving activity of replacing less precise understanding with more precise understanding. But how does one know whether a new idea represents an advance or not? How does one determine the truth? In mathematics one can offer proofs that are true, without doubt, but such absolute certainty is generally not achievable in science. So, when a new idea comes along there should be discussion and debate. Efforts should be made to refute the new idea, to show that it is not true. If the scientific community is unable to refute the idea, ideally in the same journal where it was first published, then the idea should be acknowledged and cited in the relevant scientific literature that appears afterwards.

The criterion for truth in science is different than for truth in other fields. Jurisprudence, for example, filters evidence as to whether it is admissible or inadmissible and allows a jury of ordinary citizens untrained in the law to determine truth, i.e. guilt or innocence. In matters of political governance, for example, consensus is the criterion for truth, but in science consensus is nonsense. Science is a strictly logical process, not a democratic process; with every new discovery, consensus is overthrown.

Fundamental new ideas typically meet with resistance. I have observed there is a human analogue to Lenz's law in physics and Le Chatelier's principle in chemistry, the tendency of a system to oppose change. Once, after a pleasant dinner, I began to explain my recent discoveries to a friend, a visiting scientist whom I had not seen for several years. As I described how Earth's interior differed from what he had been taught, his demeanour changed, his face became ashen, and he hardly spoke the remainder of his visit. I have encountered similar experiences with other scientists. When I am exposed to a fundamentally new concept, I ask myself, 'Suppose the new concept is correct, what does it mean? What advances might follow from it?' I try to allow a new idea the benefit of doubt before discarding it abruptly.

Good science, properly executed and securely anchored to the known properties of matter and radiation, transcends opinion. Ideally, one seeks to discover fundamental quantitative relationships in nature. In my view the making of models, based upon arbitrary assumptions, on the other hand, is not science. Furthermore, models are computer programs that generally begin with an assumed end result which is then attained by selecting variables and assumptions that yield the sought end result. Some models can prove useful, but they do not lead to scientific discoveries.

Six months into my postdoctoral apprenticeship, Suess asked me directly one afternoon if I knew why he had chosen me. I confessed I did not. Then he reminded me of my seminar and the questions that followed and one specific question in particular I had long since forgotten. He reminded me that I had answered by saying I could not answer that question, that the information was simply not known. Suess told me that not one young scientist in a thousand would have answered the way I had; most would have tried to answer the question. He then explained it is much more important to know what is not known, than to know what is known.

There is a technique, a method, one can use to begin to know what is not known: quite simply, go back in time. Travel through time, through a historical review and understanding of the events and ideas that led to the present state of understanding of a specific scientific idea. The changing movement and development of ideas is documented in the scientific literature. Logically ordering historical observations and ideas into a sequential progression of understanding, while being keenly aware of later changes and discoveries, helps one to see gaps in the sequence, to begin to know what is not known, and, in the light of later data, perhaps to find mistakes that were made and not corrected.

Science is a logical progression of causally related events, analogous to a really good movie where all the actions are logically and causally related; the pieces – the characters, their actions, and the sequences of events – all fit together. Now, if something about nature does not make sense and seems like a really bad movie – unrelated pieces just stuck together – ask the question, 'What is wrong with this picture?' That can be the first step towards making an important discovery.

There is a more fundamental way to make discoveries than the variants of the scientific method taught in schools: An individual ponders and through tedious efforts arranges seemingly unrelated observations into a logical sequence in his or her mind so that causal relationships become manifestly evident and a new understanding emerges, showing a path on which to make new observations, new experiments, new discoveries, and new theoretical considerations[1].

Science should not simply be an academic discipline without reference to the human community or Earth's biota, but should aim to improve the well-being of life on our planet. The content of *Current Science*, for example, is wholly consistent with that aim. Although the infusion of politics into funding and oversight by government agencies sometimes make it difficult, scientists should maintain the integrity that should be an intrinsic part of their profession. By virtue of their abilities and advanced training, scientists have an implicit responsibility toward humanity. That is especially the case in India and elsewhere where resources are limited and small advances and innovations can make significant improvements in the quality of human life.

1. Herndon, J. M., *Hist. Geo. Space Sci.*, 2010, **1**, 25–41.

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