GUEST EDITORIAL

MAKING AND MEASURING IMPACT IN SCIENCE

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The measurement of impact in science is a relatively recent development. For most of human history, there was no reliable method for distinguishing science from non-science, and it was necessary for such method to be developed first. The breakthrough occurred in the 1600s when, facing authoritarian opposition to their respective scientific claims, William Harvey (1578–1657) in England and Galileo Galilei (1564–1642) in Italy side-stepped their opponents by publishing their arguments. As a result, all members of the scholastic community had direct access to their claims and could evaluate them independently. During the fierce controversies that followed, the weight of peer opinion enabled Harvey and Galileo to win. It was in this manner that publication and peer evaluation first emerged as the method—so far the only dependable method—for sorting out science from non-science and for evaluating alternative claims in science. As the practice of publication began to spread, it defined modern science as an open and social activity involving the entire global scientific community.

Publication and peer evaluation works by stripping away the cover of secrecy under which fraud, wishful thinking, bias and abuse of authority can thrive. In addition, publication (a) provides a systematic global method for documenting knowledge as it develops, (b) provides a transparent mechanism—date of publication—for recognition of first discovery, (c) makes it possible for scientists to make progress by testing and building upon previous published efforts instead of repeating efforts that were never made public and (d) unites all scientists in developing a single global system of knowledge.

In publication, scientists take into account what is already published, through citation of previous works, while submitting their own claims for recognition. After publication, papers that attract attention are cited again and again and get incorporated into the mainstream of global scientific consciousness. Papers that fail to attract attention make no impact. Unpublished work has no status at all.

The pioneering scientists of the 1600s and 1700s were amateurs, but the open nature of the science they created made scientific research manageable and fundable, and prepared the way for the hiring of salaried scientists and the establishment of research institutions. With the payment of salaries, a need arose for methods to estimate the impact of individual scientific contributions. The method that has evolved during the past few decades is based on the frequency of citation of individual papers within a particular time frame after their publication. Variations of this method have been developed to measure the scientific impact of scientists, institutions, journals and countries.

For comparisons at a macro level, e.g. between countries, a simple measure has been devised, based on the practice of peer-reviewed journals to appoint two or more experts to review each paper prior to acceptance for publication. This review process weeds out inferior papers. Consequently the rate and quantity of publication in peer-reviewed journals have been used to measure the scientific impact of countries.

In a famous analysis in 2004, Sir David King, Chief Scientific Advisor to the British government found that 31 countries produced over 97% of the world's output of scientific papers in peer-reviewed journals. Of the developing countries, only India, Brazil and China were in the top 31 and they moved up to this level less than 20 years ago. The remaining 162 countries—mainly tropical developing countries—contributed a combined total of only 2.5%.

In our experience, countries that make little impact in science are those that do not recognise the central role of publication in science and have low awareness of what makes impact. Take for example an investigation in which the wood of *Acacia mangium* is subjected to mechanical tests, using material from two plantations: one 10 years old and the other 20 years old. A report describing the mechanical properties of mangium at 10 and 20 years would make little impact because it would just be a data report. An analysis showing that wood at 10 years is statistically different from wood at 20 years does not provide adequate scientific explanation. The authors need to do more, e.g. by developing a *theory* to explain the relationship between age and mechanical properties. Such a theory would *predict* properties of mangium at all ages within reason.

It is important to understand that science is not just a vast collection of observations of nature. More importantly, it is a vast collection of *theories* to explain and predict nature. The power to predict is what gives theory impact. A good theory packs maximum explanatory and predictive power in a small package whereas data lacks explanatory and predictive power, no matter how profuse and detailed. To make maximum impact, one must make theory. The following examples from Harvey and Galileo further illustrate this point.

It is common knowledge that blood circulates in the body through a closed network of arteries, veins and capillaries but this was not always common knowledge. Before Harvey, it was believed that blood changes into flesh at the extremities of the arteries and flesh changes back into blood to feed into the veins. Harvey measured the quantity and rate of flow of blood, and argued for the existence of a closed network of blood vessels, with no leakage. There had to be capillaries, too fine to be seen, to complete the network. Capillaries were not seen until the microscope was invented. By then, Harvey had died. Harvey's 'discovery' of blood circulation was therefore an interpretation of data—a scientific theory. Once Harvey's theory had gained acceptance, it became 'fact' and his original data, having served its purpose, faded into the background.

It is similarly common knowledge that the earth and planets move in orbit around the sun. This knowledge is attributed to Copernicus (1473–1543) but the real hero was Galileo, who provided the data and interpretation to support what was, until then, a theory that few people took seriously. Using a telescope, then newly invented, Galileo observed a number of 'stars' around the planet Jupiter that did not behave like stars. They were observed in different positions every night relative to each other and to Jupiter. Galileo interpreted these 'stars' as 'moons' in orbit around Jupiter. Galileo's interpretation was sensational because it undermined the prevailing theory of the earth as the absolute centre of the universe, around which all other heavenly bodies orbited. This opened the way for acceptance of the Copernican theory. Once the Copernican theory was accepted as 'fact', Galileo's data on Jupiter and its moons faded into the background.

Galileo had already become famous in his youth when he timed the oscillations of a lamp suspended from the roof of his local cathedral, using his body clock—his pulse rate—as his timer, to see if the oscillations were predictable or random. His interpretation was that pendulums keep predictable and constant time. Galileo's 'discovery' was so amazing that it was spread by word of mouth, and applied soon after in attempts to develop pendulum clocks. Galileo's theory had an easy passage because it faced no opposition from any previous theory.

Scientists are the discoverers of the modern age but discoveries made by direct observation are usually low-level discoveries. The big discoveries are made in the mind, as theories, and theories are justified by their predictive power. The discovery of new subatomic particles in physics is, in principle, not different from the discovery of new species in biology. About 1.8 million biological species are known. Each species is an interpretation based on critical comparisons of specimens and records; therefore, each species begins its scientific life as a theory. New species must be new for the whole world, not just for a particular place or country. At any time, anywhere, someone may argue for a species to be de-recognised or 'reduced to synonymy', but although specific interpretations are subject to reinterpretation at any time, taxonomy has resulted in a comprehensive explanation of how nature is organised.

The making of theory cannot be standardised because every case is different. Theory-making is perhaps best taught as case histories in scientific discovery. As a student, I found the wide-ranging case histories in WIB Beveridge's (1950) *The Art of Scientific Investigation* to be the perfect counterbalance to the narrowness of RA Fisher's

(1935) *The Design of Experiments*. Scientists need to master the logic behind sampling, randomisation, replication and statistical analysis of variation, but they also need to learn how to interpret single specimens (e.g. rare species, expensive specimens, rare phenomena), fragments (e.g. fossils), and unplanned events (e.g. disease epidemics), as well as to deal with unrepeatable conditions (e.g. field experiments in which the environment of next 10 years will not mirror the environment of the previous 10 years), distant phenomena (e.g. in astronomy) and practical constraints in time, money, working space and other resources.

Different scientists, using the same data, can produce different theories and thereby make different discoveries. A scientist with a global perspective is better equipped to make theory than one who is content to be a 'local expert'. Just as one cannot discover a new species without reference to the already known species in the world, one cannot confidently offer new interpretations or theories in any field of enquiry without familiarity with existing interpretations or theories. A study on salt tolerance of plants in Thailand is deficient unless presented within the context of salt-tolerance in plants everywhere. A study on bark insects in Central India is best presented within the context of bark insects everywhere. A study on the quality of water from an oil palm estate used as a water catchment area may seem unique for a country that grows oil palm, but the use of agricultural areas as water catchments is worldwide, and all have similar problems such as leakage of agricultural chemicals into the water supply. There is little excuse nowadays for scientists not to develop global perspectives in their areas of research.

Poor theoretical content is one of the major causes of rejection of papers by journal editors. If we chose to stay within our comfort zones, conforming to existing theories and contributing only small additional observations to existing data pools, we cannot expect to make much impact in science. Data alone is sometimes interesting enough to merit publication, but the more interesting discoveries are made through theory. To improve our ability to make theory, we need to make it a habit to see if data can be interpreted in new ways, and to learn how to present new interpretations persuasively to a critical audience of our peers.

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