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GUEST EDITORIAL

Why do we do the science we do?

In the beginning of modern science, it was human curiosity that led to exploration, formation of ideas, development and testing of hypotheses, and formation of theories that could predict. How do things work in our world? Why do they work the way they do? Can we predict how things will work in the future? Clearly, these questions were the basis of human scientific intrigue. There were discoveries, inventions and advances that went along with these inquiries. These activities were carried out by a small number of scientists, often supported by patrons or by the scientists themselves.

Some time along the way, interest emerged in not just understanding, but manipulating our surroundings. Often, this manipulation of nature or objects within our world started to be a bigger goal. Humanity has engaged in this process for its benefit for a long time – be it benefit for all or benefit for a smaller set of people. Technological advances to win wars have been major drivers in many cases. Think of cannons, gunpowder, missiles and nuclear weapons, for example. Of course, many other discoveries and emerging scientific areas followed these pursuits. Thermodynamics is a case in point; it developed upon realizing that work and heat were related while boring cannons and the generation of heat that followed. The pursuit of converting heat to work was at the inception of the Industrial Revolution. The ability to create work from energy was a major accomplishment that has driven industrialization.

During the late 1800s, science became more than a curiosity-driven endeavour. However, one could argue that this transition started much farther back. But by the 20th century this trend was clearly evident. After the Second World War, there was a line of thought that was essentially codified as to how science leads to use. Indeed, this is evident even today. It was asserted that there is a progression from the basic science to applied science and then to engineering to application and products. Often this codification is attributed to Vannevar Bush, and is a simple linear model.

This linear concept of a march towards practical use has been ingrained in many ways, including how we classify fields of research, how we fund research efforts, and how we then recognize and reward such research. For example, the US military has clear classifications of its research funds: 6.1 – basic research; 6.2 – applied research; 6.3 – advanced technology development; 6.4 – demonstration and validation, and so forth. Certainly, this paradigm is based on the linear model noted above. Moreover, this paradigm is ingrained and likely followed in nearly all fields of research, all over the world.

There is another way to think about this progression towards application and product. The microbiologist Louis Pasteur is famously quoted as saying: 'There are no such thing as applied sciences, only application of science.' This is a different thought process than the linear model. Indeed, Donald Stokes in his seminal book *Pasteur's Quadrant*[1] argues that there is a different way to look at research and transition of research to application than the linear model noted above.

Stokes[1] classifies our pursuit of knowledge into quadrants (Figure 1). Clearly, pure basic research is done solely for the advancement of knowledge, with little or no concern to relevance for immediate applications. It is important to remember that the emphasis is on the immediate applications. We all know the enormous eventual relevance of pure basic research to our current technology and perception of world around us – be it the atomic theory or recognition of the structure of DNA or infinitely many other discoveries. Stokes named it the Bohr quadrant after Neils Bohr, one of the fathers of atomic theory. The premise here is that Bohr's work was done solely for the purpose of understanding matter. The fact that Bohr's ideas were central to the development of the nuclear bomb, nuclear energy or nuclear medicine is a fallout – not the primary intent of his work.

Then, there is the work done with the sole purpose of application. Such work may advance our basic understanding, but it is not the primary purpose – the ultimate applicability is the guiding force of such an endeavour. Stokes called it the Edison quadrant, after the eminent inventor Thomas Edison. The premise here is that Edison's work was done solely for the purpose of making widgets and products that were useful and led to economic benefits. Clearly, there were advances in our knowledge as a result of this work. However, in this case they were fallouts of the work, rather than the intent.

Then, there is the top right quadrant – where the goals are relevant *both* to advancing our knowledge and to the

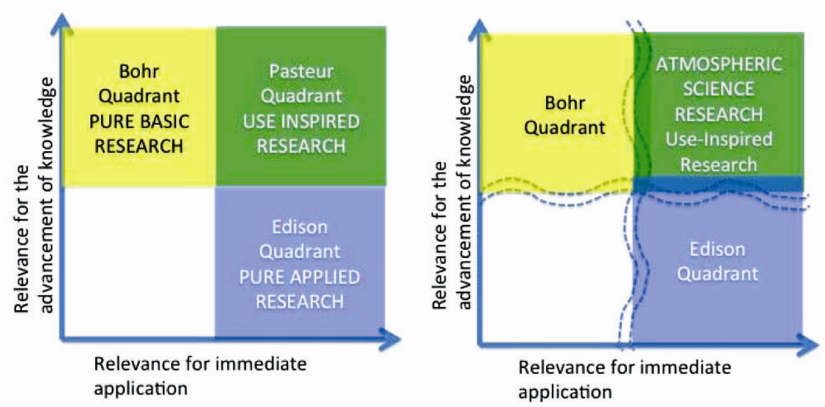

Figure 1. (Left panel) Separation of research into quadrants based on their relevance for advancement of knowledge and relevance for immediate application. These axes have been alternatively labelled as quest for fundamental understanding and consideration of use (adapted from Stokes[1]). (Right panel) Author's rendition of these quadrants with the assertion that atmospheric science falls into Pasteur's quadrant and that the separation between the quadrants is not rigid as shown by the overlaps and the fuzzy separators.

immediate application. Stokes called this Pasteur's quadrant which is *use-inspired*. (This is not to be confused with user-inspired.) Working in this quadrant, scientists have goals of advancing science to provide immediate useful results. (Of course, there is the fourth quadrant, which we will not even discuss.) The lines that separate these quadrants are indeed fuzzy. As shown in Figure 1 (right panel), they are likely to be in the eyes of the beholder. However, this classification has some major attractive features as well as ramifications.

Now science has become a profession with a large number of active scientists; it is not merely an activity supported by patrons. Countries want to advance the knowledge base to make lives better for their citizenries. Sometimes, taxpayers fund the research efforts. Other times, industries fund research to make a profit. Either way, the expectation for a return on their investment is both logical and appropriate.

Having worked in field of atmospheric science for more than three decades, my assertion is that this field falls squarely in Pasteur's quadrant. After all, most of the atmospheric scientists claim that we work on societally relevant issues: weather prediction, climate change, air quality, water supply for food growth, to just name a few. Indeed, there are some components of atmospheric science that could be viewed as being in the Bohr quadrant (e.g. original ideas of atmospheric dynamics) or the Edison quadrant (e.g. building sensors for atmospheric research). However, because it is a new and fast-emerging field with relevance to immediate use, I suggest that atmospheric science be viewed as use-inspired research that falls squarely in Pasteur's quadrant, much in the way of microbiology or medical research. In the beginning, atmospheric science was indeed driven by curiosity. However, it has evolved to be use-inspired research.

So what does it mean to be working in Pasteur's quadrant? First, it means that the science and research we do is aimed towards an ultimate use. This has to be acknowledged. Use must be a primary motivation for the research we do. Second, there is much information that is not available; therefore, such information has to be developed. In the process, we have to stray from the goal of immediate use, but return to it as the developed knowledge advances our science. Third, this means we have to go where the needs are – not just do what interests us to fulfil our curiosity. Even though this separation between curiosity-driven science and use-inspired research is a grey area and often varies from person to person; also, the same person may be engaged in both kinds of research. (For these reasons, I have overlapped the quadrants and drawn the fuzzy separators!) Fourth, we must judge the value of the science and the researcher for producing information that is useful and used. For example, the reward system for the 'profession of research' may have to be thought out differently than just the number of papers published. Fifth, it is likely that this is a progression in many sciences. Atmospheric science was indeed originally driven by curiosity. Indeed those discoveries were pivotal for advances in much of physical science. Take for example, the discovery of oxygen in air, pressure changing with altitude, or spectral features of sunlight leading to the field of spectroscopy. Indeed, one can think of many other such features of a use-driven science that falls in Pasteur's quadrant as well as the ramifications of being viewed as use-inspired.

It is possible that many researchers in other areas also view their science as use-inspired research. So in conclusion, I ask you to ask yourself – does your research fall in the Pasteur's quadrant with all its ramification?

1. Stokes, D., *Pasteur's Quadrant: Basic Science and Technological Innovation*, Brookings Institution Press, Washington DC, USA, 1997.

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