Completing the Bush Model: Pasteur's Quadrant – *Donald Stokes*

Vannevar Bush looms so large in our historical memory of the transformation of American science over the period of the Second World War, it is small wonder that we mark the half-century of the publication *Science: the Endless Frontier*, the illustrious report that helped usher in a golden age of American science.

Rather than probe the background and drafting of that report, I will deal with the significance of the argument that Vannevar Bush set out for the making of science policy in the post-war years and the legacy of that argument for the debates over science and technology policy in our own time – the increasingly troubled dialogue between science and government today.

It would be difficult to exaggerate the degree to which the relationship between government and science was transformed by the Second World War. The federal government had been involved in scientific activities from the beginning of the republic, and by the late 19th Century, a good deal of science being done in this country was in federal establishments such as the Smithsonian Institution, the Geological Survey, and the agricultural experiment stations that were started with federal support.

However, the current model of advanced scientific studies was not spread through the country by federal establishments. It was promoted by the nascent research universities, which laid the groundwork for their preeminence in science in the 20th Century with resources gathered largely from private donors, philanthropic foundations, state legislatures, and fee-paying students.

Indeed, by the period between the world wars, there was active hostility on the part of the scientific community to the acceptance of federal support, stemming from unease about the control that such support might bring. But this hostility was dramatically transformed by the war. It was a scientific war in large part, and that effort was led by enlightened scientists, with Vannevar Bush in the vanguard.

Bush recruited a small army of gifted colleagues for the scientific tasks of the war, with full backing of the strongest president of the 20^{th} century. The Office of Scientific Research and Development (OSRD), as Hunter Dupree has noted, became as close to a General Ministry of Research as this country has ever had. And the flow of resources for scientific purposes – including basic nuclear science research that produced the weapons that decisively altered the course of the Pacific War – showed the scientific community, as it showed the nation, what might be done.

As the war drew to a close, there was agreement between the scientific and policy communities that support should continue into peacetime, but the perspective of the scientific community was based on radically different grounds. When Franklin Roosevelt requested that Vannevar Bush develop a post-war science plan, the scientific community was determined that if this flow of resources continued, the direct governmental control of the content of research should be drastically cut back. That, in the broadest terms, was the aim of the report that Vannevar Bush produced.

The means that were used to try to achieve the dual effect of continued governmental resources with reduced governmental control were partly organizational. Four background advisory panels that went to work on the problem. The most important of these was chaired by Isaiah Bowman, the President of Johns Hopkins University. That panel developed the plan of a national research foundation with the responsibility, essentially as broad as that of OSRD during the war, of channeling most of the federal grants for the support of research.

They wanted to insulate the funding from the political process by making the foundation self-governing, with a board that was drawn from the scientific community, and that would choose its own director rather than having a director appointed by the President and confirmed by the Senate. They even sought to withdraw funding from the annual budget cycle by establishing a long-term, expendable endowment that would need to be replenished only at widely-spaced intervals.

Bush revised the organizational proposals to restore the foundation to the budgetary process, but he retained the idea of the director chosen by the board. If that plan had been implemented, it would have insulated the funding of science from the political process. However, much of the significance of *Science: The Endless Frontier* lay in the fact that the means by which this dual pair of objectives was sought was not left to organization alone.

Bush also included in his report a general way of thinking about the nature of basic science and its relationship to technological innovation. This turned out to be profoundly important in the longer run, so that as the proposed organizational plan foundered, the skillful use of Bush's ideological view of those basic relationships – what we might call a "paradigm view" – was employed more and more by those who wanted to achieve the objectives that were being sought.

A great deal of the vision of the nature of basic science and its relationship to technological innovation is contained in two aphorisms in the Bush report, both worthy of Francis Bacon. Each was cast in the form of a statement about basic research – a term that was given currency by the Bush report.

The first of those aphorisms is that basic science is performed without thought of practical ends. That sounds like a definition, and a great many people have subsequently wanted to take it to be a definition, but Bush made it quite clear that the defining characteristic of basic research is its attempt to find more general physical and natural laws to push back the frontiers of fundamental understanding.

What that aphorism came to mean, instead, was that there is an inherent tension between the drive toward fundamental understanding on the one hand, considerations of use on the other, and by extension, a radical separation between the categories of basic and applied science. Bush went on to endorse a kind of Gresham's Law in which an attempt to mix the applied and pure in research was sure to result in the applied driving out the pure.

Having written that canon of basic research, Bush wrote down a second. It was that basic research is the pacemaker of technological improvement. If you insulate basic science from short-circuiting by premature thoughts of practical use, it will turn out to be a remote but powerful dynamo of technological innovation – the advances of basic science will be converted into technology by the processes of technology transfer, moving from basic to applied research, to development, to production or operations, according to whether the innovation is a new product or a process.

It is interesting to note that both those canons came to be captured by very simple, one-dimensional graphics. The first was represented by the ever-popular idea of a spectrum of research from basic to applied. The dynamic version, the second canon of basic research, was represented by the equally popular idea of the linear model that moves from basic research to applied research via the processes of technology transfer.

There was a third element in Bush's argument that has turned out to be one of great importance, that is very closely associated to the second canon of basic research. It is the notion that the nation will recapture the technological benefit of its investment in basic science.

This idea appears most clearly in the Bush report in the obverse form, in his statement that, "A nation which depends upon others for its new basic scientific knowledge will be slow in its industrial progress and weak in its competitive position in world trade, regardless of its mechanical skill." I will return to this additional element, the third part of a triad of fundamental assertions that turned out to be tremendously important in the Bush argument.

The reception of *Science: The Endless Frontier* was full of irony: the organizational plan was defeated, while the ideological view prevailed. In the five-year gap between the publication of that report in 1945 and the creation of the National Science Foundation (NSF) in 1950, the authority of the NSF, which Bush had wanted to keep whole, was shattered by the policy process.

First of all, in 1946, responsibility for nuclear science went to the newly organized Atomic Energy Commission (AEC). In 1947, responsibility for basic science bearing on the military went out to the newly organized Department of Defense (DOD).

Perhaps most tellingly of all, the responsibility for biomedical and health research which had been part of OSRD during the war, went to the National Institutes of Health (NIH), as what had been a small in-house laboratory was reorganized into a much larger in-house complex and the huge flourishing external grant agency that we know today. So that when the NSF was created in 1950, it had the much narrower mission of supporting largely pure scientific research, largely in the university sector.

The irony is deepened by the fact that the defeat of the organizational plan made it more likely that the ideological view would triumph. Indeed it is likely that the cluster of ideas Bush outlined would have been only partially noticed in that report had it not been needed for the purpose the scientific community and its allies in the policy community wanted to achieve – independence from federal control – and this could not be achieved by the organizational plan.

Indeed, only when the organizational responsibilities for science were shattered and fragmented could the DOD use the Bush outlook to cement its relationship with the universities. In 1948, an enterprising reporter for Fortune Magazine went to a meeting of the American Physical Society and found that 80 percent of the papers being presented at the meeting were supported by the Office of Naval Research. At the onset of the Cold War, it was deemed essential to restore the status-quo ante of the second world war for a wide part of the basic scientific community. And when the NSF was created in 1950, it could happily endorse the view that pure research is the ultimate font of new technology, a view that was very congenial to an agency whose narrow limited function was to support basic research.

Indeed if Bush's National Research Foundation – with responsibilities almost as broad as OSRD's – had been created in the immediate aftermath of the war, the first of Vannevar Bush's canons, that basic research is performed without thought of practical ends, would almost certainly have come under intolerable pressure as the agency attempted to build and fund research agendas that met all of the scientific needs of the federal government.

There is very little doubt that the vision that was set out in *Science: The Endless Frontier* soaked into the scientific community very deeply, and into the policy community as well. If you want evidence of that, it might be clearest in the country's response to the launching of Sputnik in 1957. One might have imagined that our response to that technological surprise by the Soviets would be largely technological – that we would build bigger booster rockets and all the rest and, as we did ultimately, put a man on the moon.

But what is really significant about the country's response is that we regarded it not just as a challenge to a piece of our technology, but as a general scientific challenge. The years after Sputnik were years of soaring budgets for almost all branches of science, so that the technology coming out of the other end of the pipeline, according to the linear model, would be our technological surprises and not theirs.

Admiring as we all can be of the success of the paradigm view set out in *Science: The Endless Frontier* and its ushering in of the Golden Age of American science, the incompleteness of this view of the nature of basic science and its relationship to technological innovation has been increasingly clear.

Let's first of all return to the first of Bush's canons, that basic research is performed without thought of practical use. The rise of microbiology in the late 19^{th} Century is a conspicuous example of the development of a whole new branch of inquiry because of considerations of use, not only the quest of fundamental understanding.

There is no doubt that Pasteur wanted to understand the process of disease at the most fundamental level as well as the other microbiological processes that he discovered, but he wanted that to deal with silk worms, anthrax in sheep and cattle, cholera in chickens, spoilage in milk, wine and vinegar, and rabies in people.

The melding of those motives in the work of the mature Pasteur is so complete that you could not understand his science without knowing the extent to which he had considerations of use in mind. The mature Pasteur – not the crystallographer at the dawn of his career, the man who took on the enigma of recemic acid at the *Ecole Normale* – embarked on a pure voyage of discovery. But the mature Pasteur never did a study that was not applied while he laid out a whole fresh branch of science.

And that example is not a solitary one. Lord Kelvin's view of physics was profoundly industrial and inspired in substantial part by the needs of empire. The work of the synthetic organic chemists, German and then American, over the turn of the century as they laid the basis of the chemical dye industry, and later, pharmaceuticals, was equally a melding of those two motives. Keynes sought an understanding of economies and their dynamics at the most fundamental level, but he sought that to lift the grinding misery of depression.

The creators of modern analytical demography have always regarded population change not only as a process that challenged understanding on a fundamental level, but as a problem with immense human consequences. Both the molecular and non-molecular ends of modern biology are profoundly influenced by scientific and applied objectives at once. And the earth sciences have always been influenced by natural disaster and economic gain. Indeed, every one of the basic scientific disciplines has its modern form, in part, as the result of use-inspired basic research. We should no longer allow the post-war vision to conceal the importance of this fact

Since that post-war vision has been kept in place, in part by very simple graphic images, I have created a little bit of graphic reasoning to try to move one step in a more realistic direction. This array presents a new model of scientific research, which provides a more accurate depiction than Bush's linear model. I call it "Pasteur's Quadrant."

Research is inspired by:

		Considerations of use? No	Considerations of use? Yes
Quest for fundamental understanding?	Yes	Pure basic research (Bohr)	Use-inspired basic research (Pasteur)
	No		Pure applied research (Edison)

(adapted from *Pasteur's Quadrant: Basic Science and Technological Innovation*, Stokes 1997).

If we were to return to the spectrum of basic to applied and ask ourselves where Louis Pasteur is on that spectrum, you might think initially that he is somewhere near the middle because he cared about both those goals at once. But that would be clearly mistaken.

You might conclude that he belongs way out toward the basic end of that spectrum, but he also belongs way out toward the applied end of the spectrum. Thus the anomaly of the mature Pasteur as two Cartesian points in this Euclidean one-space. If we want to stay with the Euclidean framework and eliminate this anomaly, we must grasp that spectrum in the midpoint and fold the left-hand end of it through an arc of ninety degrees. This restores Pasteur to the status of a single-Cartesian point in what is now a two-dimensional conceptual plane, with the vertical dimension representing the degree to which a given body of research is motivated by the quest of fundamental understanding, and the horizontal dimension the extent to which it's motivated by considerations of use.

There is not the slightest reason why these questions should be treated in dichotomous terms, but since the whole world loves to think in terms of dichotomies, then it's plain we have a double dichotomy.

Take a moment to consider the quadrants that are presented. The one at the upper left is for the pure voyages of discovery, the voyages of Newton. Let me call it Bohr's Quadrant, since there were no immediate considerations of use in mind as Niels Bohr groped toward an adequate model of the structure of the atom; although note that when he found it, his ideas remade the world.

The quadrant at the lower right might be called Edison's Quadrant since Edison never allowed himself or those working with him in Menlo Park five minutes to consider the underlying side of the significance of what they were discovering in their headlong rush toward commercial illumination.

Edison himself one night heated up a filament in a vacuum and observed what is now known in American physics as Edison's Effect because he wrote it down in his notebook. I owe to Nathan Rosenberg the observation that if he had tried to consider its more fundamental implications, he might have shared the Nobel prize with J.J. Thompson for discovering the electron, but he went right on.

But there certainly is "Pasteur's Quadrant," for work that is directly influenced in its course both by the quest of fundamental understanding and the quest of applied use – the sort of quadrant that supplies a home for what Gerald Holton has called, "work that locates the center of research in an area of basic scientific ignorance that lies at the heart of a social problem."

Now I will not comment on the fourth quadrant. Naming it is a growth industry, but I would just note in passing that it is not empty. And the fact that it is not empty helps to make the point that this is not a more elegant version of the traditional basic-to-applied spectrum, that we genuinely have a two-dimensional, conceptual plane.

Examples are equally plentiful that contradict the very simple dynamic linear model. One reason we can be sure that basic science is not simply exogenous to technological innovation is how often modern science is explaining phenomena that are found only in the technology.

An example of this process from earlier in the 20th Century is the work of Irving Langmuir, who became fascinated by the surfaces of the electronics components that were manufactured by General Electric and its other firms. It would not be right to say that the several billion-year history of the universe had not presented any analogs of those surfaces, but the human race had never seen them. The scientific community had never seen them until they appeared in the technology.

Langmuir, as he earned himself a Nobel Prize for working out their surface physics – a fundamental advance in physical chemistry – also laid the basis for patents by General Electric that secured its market position for years to come.

That example is one of an increasingly large number. Another would be the ongoing effort of the condensed-matter physicists to see whether semi-conductors can be built atomic layer by atomic layer – something that will require a fundamental advance of science to do – but focusing on phenomena that would not have been seen absent the miniaturization of semi-conductors with their astonishing increases in speed over several decades' time.

Indeed, we're going into the 21st Century with two closely interwoven trends: one, which is commonplace, is that more and more technology will be science-based. The other, which is still very widely under-appreciated, is that more and more science will be technology-based in just the sense that I've expressed and not merely in the sense of instrumentation, which has been important in Western science at least since the time of Galileo.

If we were to present a rival image for the one-dimensional linear model, it would be much more like the rise in fundamental scientific understanding and the rise in technological know-how as two loosely coupled trajectories. They are loosely coupled because the increase in scientific understanding is, at times, the result of pure science with very little intervention from technology, while the increase in technological capacity is often the result of engineering, design, or tinkering at the bench, in which there is no intervention by fresh advances of fundamental science. But at times, each of those trajectories profoundly influences the other. The influence can go in either direction with use-inspired basic research often cast in the linking role.

The experience of recent decades also has called into question the third of the elements of the vision in *Science: The Endless Frontier* to which I've referred, which is that the nation can expect to capture the technological return from its investment in basic science.

If we had been sitting at Vannevar Bush's elbow when he wrote, "A nation which depends upon others for its new basic scientific knowledge will be slow in its industrial progress and weak in its competitive position in world trade, regardless of its mechanical skill," we might have said, "Now just a moment, Dr. Bush, elsewhere in your report you've noted that the Yankee ingenuity borrowed the science of Europe to make great industrial strides – indeed the greatest in our economic history." But in the post-war world, with the U.S. so much in the ascendance both in science and technology, no one asked that question.

It has been asked increasingly insistently since, as the Japanese have repeated that historical lesson, making the greatest industrial strides while they continued to be substantially behind this country and Europe collectively in basic science. It has been an increasingly skeptical point in the policy community as to whether the investment that they are asked to make in pure science will bring a technological return that will be ours and not someone else's.

However much we may admire the foundation for post-war science that was laid by *Science: The Endless Frontier*, the bargain that was struck at that period between science and government was bound in the longer run to be a Faustian one.

If the society was told that a heavy investment in pure science would produce the technology to handle a full spectrum of society's needs, it was bound several decades later to stop and say, "Now just a moment, we have some unmet technological needs. Indeed, we have some that have been created by the technology spun off of your science – the deal is off."

Echoes of that view can be heard in the speeches of even such a great friend of basic science as George Brown, the former Chair of the House Science, Space and Technology Committee. Echoes can be heard in what Senators Mikulski and Rockefeller have said to the Forum on Science in the National Interest convened by the Office of Science and Technology Policy (OSTP), and in the white paper released by the British government.

The time has come to cut into an increasingly troubled dialogue between the communities of science and government with a fresh, more realistic formulation of the actual nature of basic science and its relationship to technological innovation. This would very much accent the importance of work in "Pasteur's Quadrant."

This more realistic vision is profoundly in line with Vannevar Bush's actual career. One of the lasting ironies about *Science: The Endless Frontier* is that the vision set out in it was so different from the genius of Bush's career as scientist-engineer and research administrator. From the beginning of his career, Bush showed his skill in bringing together judgements of societal need and of considerations of use and scientific promise.

That was certainly the key to how creative he was in national government, from the time, in the late pre-war years, when he became Chair of the National Advisory Committee on Aeronautics, to the dusk of his career when he Chaired the joint Research and Development Board for the Secretaries of War and the Navy.

In terms of our present experience, we have got to learn how to bring together authoritative judgements of societal need. In a representative democracy, those have to relate to the centers of legitimate authority in the White House, the Congress, and the nation, with absolutely rigorous and first-class judgements of scientific promise. That will require a set of institutional arrangements and processes.

The savage budgetary pressures we will have at least into the 21st Century are part of the reason why we must attempt to develop a fresh contract between science and government. It must make the case for continued societal investment in realistic terms of the problemsolving capacity of science, terms that command the support and enthusiasm of the policy community and the country behind it.

While I believe it's time to depart from some of the vision that was crafted in *Science: The Endless Frontier*, this does not represent any sort of wholesale rejection of the legacy of Vannevar Bush.