**The Arc of Science**

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(Preliminary and incomplete)

The starting point for any discussion of science policy is Vannevar Bush's famous report to President Roosevelt, *Science: The Endless Frontier*. This piece has a wonderfully evocative title. It's too bad that what it says is wrong:

> [...] Basic research leads to new knowledge. It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn. New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science. [...] Today, it is truer than ever that basic research is the pacemaker of technological progress."

This quotation outlines what has come to be known as the "Linear Model" of innovation, with basic research at the upstream end of the line and practical applications at the other.

As Nathan Rosenberg has written, "Everyone knows that the linear model of innovation is dead. That model represented the innovation process as one in which technological change was closely dependent upon, and generated by, prior scientific research. It was a model that, however flattering it may have been to the scientist and the academic, was economically naive and simplistic in the extreme. It has been accorded numerous decent burials, and I do not intend to resurrect it only to arrange for it to be interred once again."

Alas, like the Meryl Streep character in movie "Death Becomes Her", the model nevertheless shows great vitality. It implicitly, but powerfully, continues to guide many discussions of science policy.

Sometimes it takes an image to beat an image. My goal in this discussion is to present an alternative image: an arc that starts at the level of everyday experience, moves up to higher levels of abstraction, and then returns to the world of everyday experience. Along the way, I will comment on the importance of abstraction as a fundamental process in science, but also on the equally if not more important reverse journey back to the level of everyday experience or application. This discussion builds on the influential analysis of Donald Stokes, which centered around an alternative image invoked by the title of his book, "Pasteur's Quadrant." Stokes concluded that we need more scientists like Louis Pasteur – scientists who complete the arc by focusing on fundamental scientific inquiries that nevertheless have very immediate, practical, real-world applications.

From an economic perspective, it remains the case that division of labor increases efficiency, and it is not necessary for the arc to be completed by a single person like Pasteur. However, if we aim to complete the arc – to bring abstract research generated by real-world observations back down to the real world for practical application – the individuals who work in real-world contexts in the one camp, and those who work at high levels of abstraction in the other, need to be committed to communication on the upward and downward portions of the trajectory.

Finally, I will attempt to draw conclusions for policy– in particular, for policy in low- and middle-income countries. In short, the arc model reinforces the presumption in favor of weaker intellectual property rights at the downstream end, coupled with subsidies not just for basic science, but also for everyday innovation.

A key assumption of the linear model is that there are weak property rights on ideas developed at the most abstract level. As a result, governments it suggest that should use subsidies to encourage basic research at the upstream, abstract end of the line. Implicitly, it suggests that the government can rely on standard market mechanisms like property rights at the downstream, concrete end. However, if the arc starts at the bottom (the concrete), strong intellectual property protections at this level could limit the type of scientific process that ultimately lifts up ideas to higher levels of abstraction and then drops them back down into unexpected domains. Therefore, the arc model would argue for weaker intellectual property protections, even at the concrete end of the spectrum.

Second, policy must encourage the development of new ideas at this concrete end, not just at the abstract end. If IP protections were weakened as suggested, market incentives for innovation even at the most applied level would be too weak.

Of course, this second policy suggestion runs into the predictable (and well-founded) objection that governments often fail when they try to pick specific applied projects and subsidize research *outputs* in these areas. A prototype of this approach is the clean car initiative started in 1993 under the Clinton Administration, known as the "Partnership for a New Generation of Vehicles." The goal of the program was for the Big Three automakers to produce environmentally friendly cars with triple the fuel efficiency of contemporary vehicles, driven by over a billion dollars in taxpayer-funded research. The program notably excluded foreign auto manufacturers, such as Japanese competitors – the only companies that have brought hybrid vehicles to the market today. In the United States, allure of these programs is bipartisan. In 2003, the Bush administration introduced its own billion-plus program, the Hydrogen Fuel Initiative, for the next big thing, hydrogen and fuel cell technologies. (If they aren't formally excluded, let's hope the Japanese car makers refrain from participating.)

There is, however, an alternative approach, one that relies on government subsidies for the production of research *inputs* – scientists and engineers, most of whom would work in private sector firms on concrete problems. It is an approach that seems to have worked well for the United States throughout its development, including the critical period before World War II. The arguments offered here suggest that his second approach could increase economic output and encourage progress in basic science.

1. Abstraction, Math, and Language

We see abstraction at work in all types of science, including economic analysis. Because this is the part of science that we are most familiar with, it is easiest to illustrate the operation of abstraction with two economics-oriented applications. One is from a paper of mine, and the other from a paper by Nathan Rosenberg. I suspect that you will be able to tell which is which:

> [1]
>
> The production of basic science depends on the amount of scientific talent $S^B$ devoted to this activity, its own level *B*, and any of the intermediate inputs $X$ that are available for use:
>
> $$\dot{B} = B(S^B, B^B, X^B).$$

> [2]
>
> Techniques such as beneficiation which made possible the exploitation of low-grade taconite ores, improvements in sulphate pulping technology which made it possible for the wood pulp industry to exploit the fast-growing southern pine which was previously unusable, the improvement of boiler designs to prevent leakage at higher temperatures, the development of new alloys with higher melting points – all these are developments of little scientific interest, dealing as

> they do with the detailed characteristics of a material or process under very specific circumstances. Yet it is precisely such forms of technological knowledge that are directly responsible for generating improvements in productive efficiency. Economists who regard such problems with disdain and who fail to enquire into conditions which influence the rate at which such specific forms of knowledge are accumulated and applied, will necessarily remain ignorant of a major source of productivity growth.

These quotes illustrate the two ends of the abstract-concrete spectrum, and do so in two different ways. The first refers to the most abstract form of discovery: basic science. It also uses the highly abstract language of formal theory and mathematics to talk about basic science. The second focuses on the more concrete processes of discovery that are essential for economic progress. It describes them using the methods of the historian operating at the more realistic level of every observation. It refers to people and things that have names.

The processes that link the abstract and the concrete are of great interest to economists who want to understand economic progress. They are also the methods that we, as scientists, use to understand this, or any other, phenomenon. In both domains – economic progress and economic analysis – an iteration back and forth between the concrete and the abstract is essential. When economic and policy analysis proceeds entirely at the abstract level, it can lead to bad models like the linear model and bad conclusions such as that government subsidies should be directed only at research in universities, with a preference for more basic science.

The important role played by feedback from concrete applications to abstract research has been widely noted. The recent exposition by Donald Stokes puts this flow at the center of the analysis. Stokes starts with a 2 x 2 diagram. In its quadrants, he identifies three prototypes of scientific researchers based upon two factors: (1) whether their research seeks fundamental knowledge, and (2) whether their research is inspired by practical use. Niels Bohr is his exemplar of kind of basic scientist imagined by Bush, someone who seeks fundamental knowledge with no concern for how it might be used. Thomas Edison was inspired by use but unconcerned with fundamental insight. Luis Pasteur is the pivotal figure – a scientist who pioneered fundamental research on microbiology because he was inspired by such practical problems such preserving the food that soldiers carried or protecting vineyards from disease.

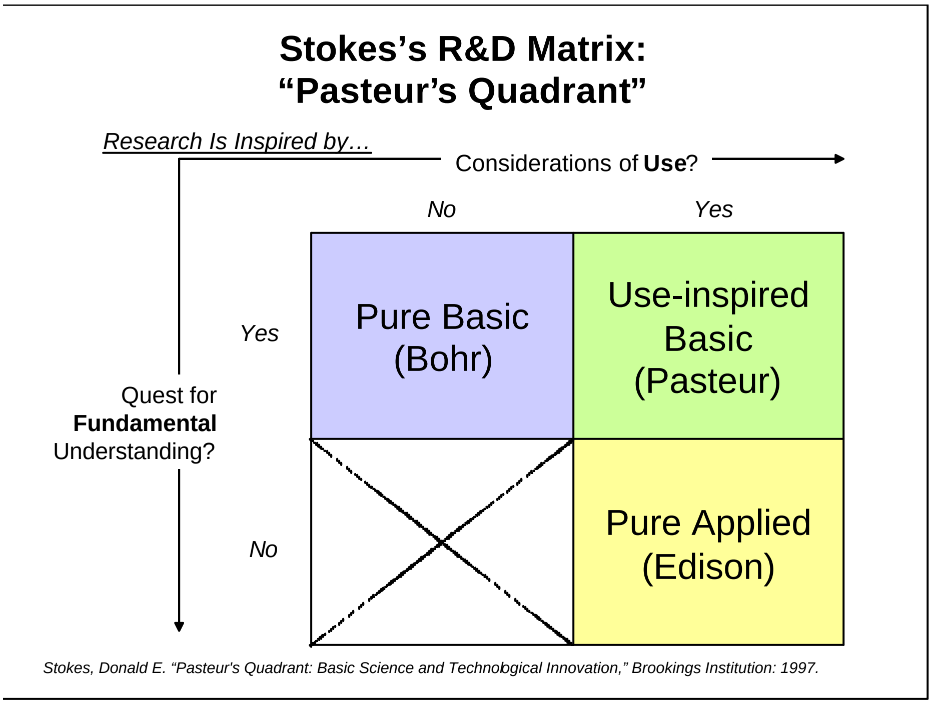


*Figure 1*

Stokes emphasis on the centrality of work like Pasteur's is convincing, but his image of Pasteur's Quadrant does not adequately capture the dynamic that starts with concrete details like "beneficiation." A fuller account needs to incorporate the process of abstraction that strips away all context, leaving a small number of basic concepts that can be linked together very precisely. With new insights derived from careful analysis of these concepts, scientists can then add back in the concrete details. This step returns them back sometimes to the original problem. But as often as not, it lands them instead in some new and seemingly different context – seemingly different, but with deep connections to the underlying concepts revealed by the abstract analysis.

There is no better illustration of this “round trip” than the study of celestial mechanics, which was motivated to a large extent by the practical demands of map making and navigation on the high seas. It is no accident that observatories were funded by the world's navies.) Early seafarers had solved the problem of determining their latitude while at sea by observing the heavens. Perhaps, they surmised, they could use these same heavens to solve the vexing problem of longitude. It was from this very practical concern that ultimately sprang one of the most striking examples of abstraction in all of science: the formulations of Newton's laws of motion. Using celestial observations turned out to be a dead end. (For an account of the extent to which the scientific establishment of the time had been convinced it would work, and its hostility to the ultimate solution based on timekeeping, see Sobel’s work *Longitude*, 1995.) But the original inspiration based on the potential for use, imparted to work on this problem a rigor and urgency that ultimately had implications that were far more important than solving the original problem.

We can better understand the underlying dynamic process if we align another of Stokes’s figures along axes that show time and degree of abstraction. (Stokes presents a figure with the dynamics, but without the attention to abstraction.)

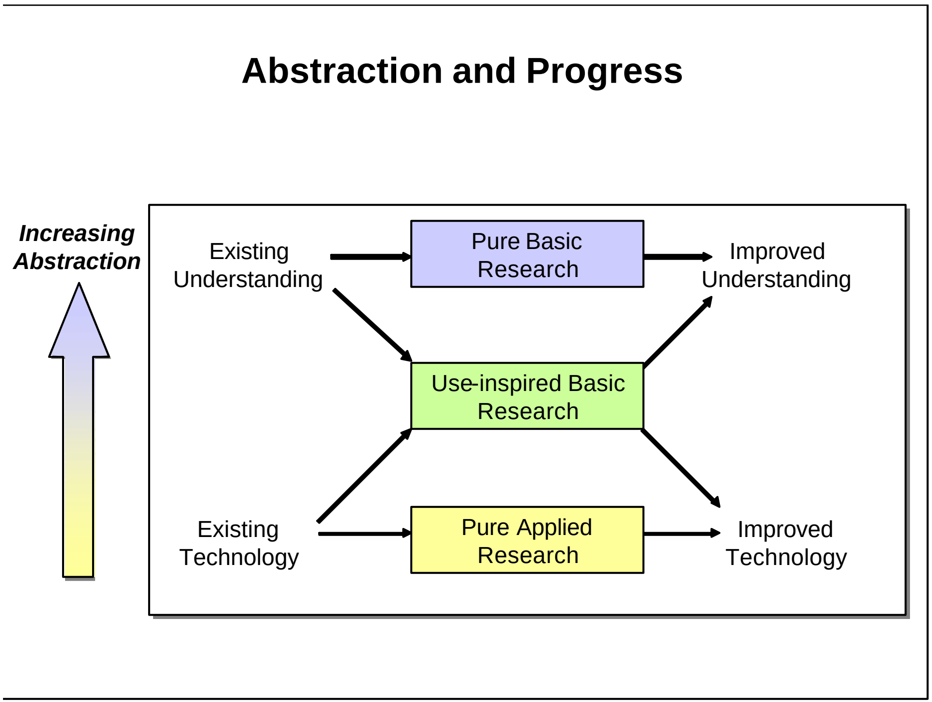


*Figure 2*

This presentation still highlights the central role scientists like Pasteur played, with their work on the intermediate category of "Use-inspired Basic Research." The arrows suggest many possible paths , but the label for this middle ground singles out a few for special attention. (He could have, but did not, give it the label that the linear model would suggest: "Basic Research-inspired Applications.")

Figure 3 highlights these special paths – ones that start from a more concrete level of analysis, then strip away the context and details to examine the essential elements in the problem, and then put the insights from this abstract analysis back to work:

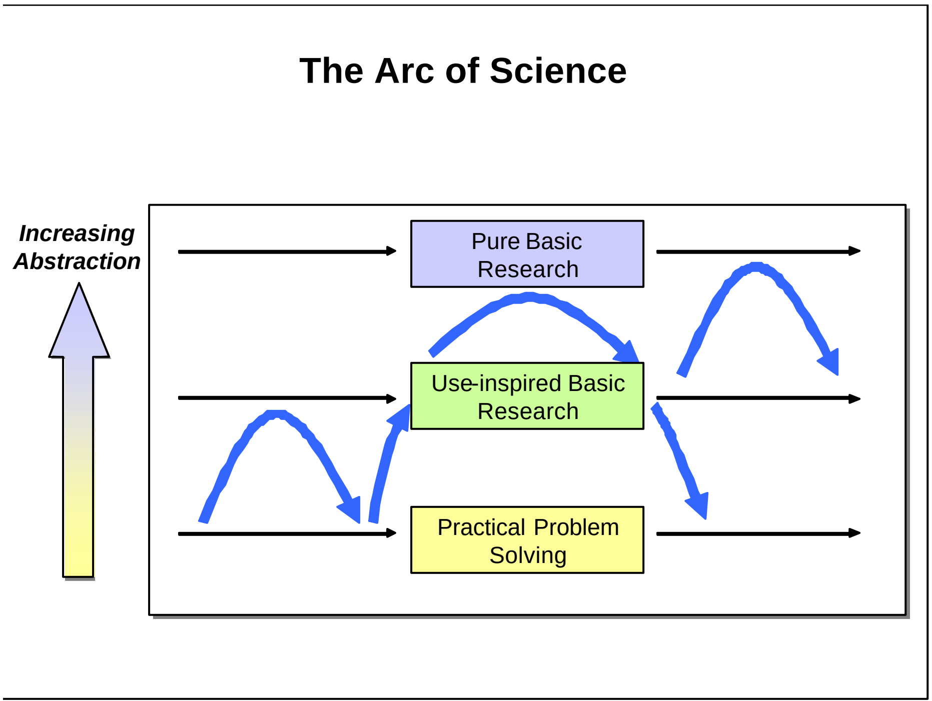


*Figure 3*

Figure 4 (below) illustrates these same paths in a slightly different way: it distinguishes the different levels not by descriptions of the activities carried out at each, but instead by the kind of discourse carried out at that level. At the lowest level, people working for Texaco, building a plant in Louisiana, may want to find a better way to refine oil into gasoline. The chemical engineers they employ may identify key abstractions such as the process labeled "distillation," thereby linking the Texaco refinery's problems to those faced by other people who are trying to get whiskey from sour mash. Finally, other engineers may formulate mathematical representations of the distillation process, and link them to fundamental equations that describe the relationship between heat, temperature, pressure, and phase transitions. Each of these steps represents further abstraction on a practical problem – abstraction which can reveal fundamental similarities to problems, and thus potentially solutions, faced by other disciplines and contexts.

This new perspective has important implications for our positive scientific understanding of how science progresses. If the dominant pathway started with basic research, which evolved according to its own internal logic, the direction of scientific progress would not be influenced by developments in the world of commerce. Yet as Rosenberg has recently argued, the case of navigation and celestial mechanics is the norm, not the exception. Even now, the direction of basic scientific research in large parts of our scientific enterprise is determined by the practical problems of the day. The focus of the discussion here is not so much the inaccuracy of the positive implications of the linear model, but its inadequacy as a guide to policy.

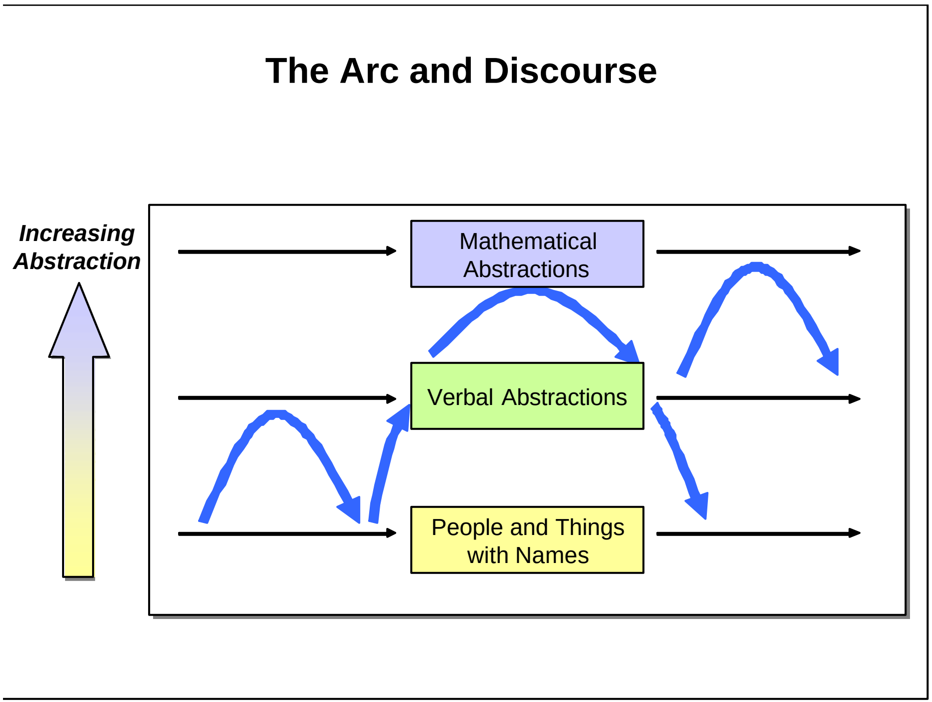
The Arc and Discourse
Increasing Abstraction
Mathematical Abstractions
Verbal Abstractions
People and Things with Names

*Figure 4*

## 2. Lost in Hilbert Space

The lesson that I draw from Stokes is that science moves forward when it arcs up to a higher level of abstraction, and then adds back the detail and context necessary to put any new insights to work in the so-called "real world." This has implications for the kinds of institutions that governments should use to support science, implications to which I will return. It also, parenthetically, has implications for how we as economists do our jobs.

When the field of economics went through its wrenching transition from verbal discourse to formal mathematics, there was, understandably, open resistance and real concern about the payoff from this new higher level of abstraction – abstraction that, based solely on the arc up, looked like abstraction for its own sake. Had the traditionalists won the day and prevented this upward arc from manifesting itself, scientific progress in economics would have been significantly retarded. (In retrospect, one wonders why it took so long. Physicists were centuries ahead of economists in their use of mathematical formalism, and interlopers like Frank Ramsey offered to help.) But now that this transition is complete, the more likely impediment to further progress is that we pay too little attention to the re-entry or "landing" process that links the abstractions back to practice.

In those cases where the trajectory has already been completed, our understanding has advanced at both the most abstract and most practical levels. Consider how we have applied the tools of general equilibrium theory to better understand the practical problems of modern finance. In this instance, theory grew richer when it was forced to bring time and risk into its formal framework. (Absent this practical concern, we might instead have spent even more energy proving existence theorems with even weaker assumptions about consumer preferences.) Practitioners trading options now have new tools for doing their jobs.

When the loop was not closed, progress was slower. Looking back, we missed the opportunity to take our formal models of growth seriously in the analysis of economic history and government policy. Taken literally, models based on exogenous technological change had policy implications that lined up squarely with Vannevar Bush's conclusion from the linear model: subsidize the part of the discovery process that could most plausibly be described as being unaffected by practical concerns and market incentives. Bush himself set the stage for this connection with his claim that not only was basic research the spring from which progress flowed, but that it was also "performed without thought of practical ends."

To people who were working in the world of context and detail – historians seeking to understand the history of technology in general or of growth in the United States, or policymakers deciding how best to treat disease or to develop the technologies that the military wanted – to all of these people, Bush's claim, and the model's implication, were plainly false. Its key implication was falsified any time the model was brought into contact with detail and context. Yet because the theorists one paid attention to the concerns of the very people in closest contact with these details – and perhaps driven by a belief that models should not be taken too seriously – growth theorists remained comfortably at the level of mathematical abstraction. They made the trip up, but never came back down.

## 3. Policy Implications

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