PHYSICS, TECHNOLOGY and ECONOMIC GROWTH

Science, Technology and Economic Growth Committee of POPA
(contributed by:
J. C. Tsang, H. D. I. Abarbanel, G. A. N. Connell, L. J. Lanzerotti, and J. D. Sullivan)

"Because of the complexity of the innovation process, determining precisely the qualitative or quantitative benefits to society from individual research projects has been difficult. Although observers strongly suspect a positive correlation between investment in R&D and economic growth, the exact nature of the relationship remains elusive." (Ref. 6-2, p 2.)

1. INTRODUCTION

This bibliographic essay provides APS members with readings on our current understanding of how scientific and technical knowledge creates value in today's economy. For many physicists, who "know" that knowledge is "valuable," this subject is trivial and pointless. However, a strong public appreciation of the value of physics research and scientific knowledge is critical for continued support for such work. Knowing how this support has evolved since before WWII, and what economists, policy "wonks," political leaders, and business managers now think about the economic benefits of such support, is essential to understanding today's pressures on physics research and education. A detailed understanding of the practical value of physics knowledge in the contemporary economy and the ability to communicate that understanding to the government and business has been and will be essential in justifying federal and corporate investments in R&D.

Such efforts are necessary because the financial scale of support for R&D in the US is substantial. It is sufficiently large that if it is taken for granted by physicists and others who directly benefit from it, it can be significantly reduced. Many physicists think of US support for R&D in terms of the $3 billion dollars authorized for spending last year by the NSF and the 6.1 programs of the Defense Department. This is wrong. It is estimated that this year, $215B will be spent on R&D by the public and private sectors. Throughout the 1990s, more than 2.5% of the US GDP has been spent annually on R&D. Total US R&D expenditures since the late 1970s has doubled. This growth has been driven by industry which now provides over 65% of all US funding for R&D, reversing the pattern of the 1960s and 70s where about 60% of all US R&D spending was supplied by the Federal government. Although federal support for R&D is now at the same levels as in the early 1980s, the $63B estimated federal spending on R&D in 1998 remains an impressive part of the total discretionary federal spending. Even the $15B spent annually by the Federal government on what the White House Office of Management and Budget defines as “basic research” (including medical and biological but not all of NIH), is a measurable fraction of the total discretionary federal budget. In contrast, total Federal funding for the arts and humanities recently was only $350M, even before the wave of interest in deficit reductions. Within the federal funding context, it would be foolish not to ask why has science and technology been able to attract so many dollars. Within the context of the US economy, it would be unwise to ignore the growth in private sector support for R&D over the last two decades and not to try to understand the opportunities it presents.

As physicists, we believe that physics education and research benefit society in numerous intangible and tangible ways. For us, the intangible contributions of physics include an ever more fundamental understanding of the physical universe and the satisfaction of the deeply human instinct to comprehend the order and majesty of the world in which we live. For most APS members, the fundamental contributions of modern physics to telecommunications, medical diagnostics, energy efficiency, electronics, etc. make an unchallengable case for how physics has enriched the nation. While we may not have built the things we see around us, we know they are based on our ideas. For many of us, the intellectual beauty and anecdotal connections amply justifies the national investment in our educations and work.

While we may wish to justify physics on intangible intellectual grounds, members of the APS must recognize that more tangible rationales have always been critical to their fellow citizens, who pay the taxes that support physics research and education, and to industrial leaders, including stockholders, who devote a portion of their profits to research investments. After WWII, the most compelling arguments for the support of physics were its perceived ability to enhance the national defense and to revolutionize everyday life. Today, the need to improve our warfighting capabilities through new weapons is reduced. There is also a greater sophistication about the linkages between new scientific knowledge and the new products and processes that constitute economic growth. Most analysts agree that scientific discoveries based on research are necessary but almost never sufficient foundations for new technologies and economic growth. While many new products and processes have some origins in scientific discoveries, the scientific discovery is often far from the most "important" or "difficult" of the steps leading out of the lab and into the world. It is almost never a sufficient step for the civilian marketplace. The "I didn't actually build it, but it was based on my idea" rationale now produces scorn rather than respect. These new beliefs challenge many of the assumptions that were the foundation of post-war US R&D policy and the high level of financial support for physics.

Our readings on the relationships among scientific research, technology, and economic growth include anecdotal approaches to the problem, more qualitative general treatments, and detailed quantitative treatments. Two subjects are at the heart of the essay. One is whether the existing organization of research in the US, and the system for its support, provides satisfactory economic returns given the current level of investment in R&D. The second is the effort to quantify the economic benefits of scientific research.

The debate over the first question challenges the traditional distinctions between basic and applied research and development and the importance of basic research as a major driver of industrial innovation. It suggests that the systems and organizations that have been tremendously successful in the years following WWII may require significant modifications to meet the challenges of today's economic, political and social circumstances. As a prime beneficiary of the successes of the past, and given the physics community's strong links to the argument that the fundamental understanding of nature is the critical step in creating economically significant inventions and processes, this challenge can severely impact support of physics research as it exists today.

With respect to the second topic, our readings show there is wide acceptance that research is necessary for economic growth and many possible ways of demonstrating this. However, there is no general consensus on how the economic benefits of research can be quantified. As a result, most contemporary arguments about the economic impact of support for physics research are qualitative. The intellectual infrastructure connecting specific levels of research support to quantitative increases in the GDP simply does not exist. In contrast, analysts believe that we quantitatively understand the economic consequences of many other types of investments. Since budgets are quantitative instruments, there are significant advantages in being able to relate quantitative results to the quantitative inputs of resourses. As individuals trained to think quantitatively, we must take seriously the efforts of economists and policy analysts to quantify the economic contributions of research and education.

In sections 3-7 of this list, we suggest a number of readings which directly address the above questions. However, we begin in section 2 with a number of historical readings. Readers who recognize that times and institutions change can ignore these readings. Readers who believe that the organization of US science in the years following WWII until the last decade was divinely ordained, and perfect, should explore the readings in section 2. In section 8, we provide guides to a number of on-line resources with statistical information about the scope and scale of the US R&D effort. In Section 9, we acknowledge the traditional anecdotal justifications for the support of R&D. Many of our references are available either in full or abbreviated on the Internet. While we provide some descriptions of the non-Internet material, we provide minimum descriptions of the Internet material and hope that readers will "try them out."

Our objective is to acquaint APS members with the current understanding of how physics research and education contribute to our national wealth so that they can participate effectively in local discussions of this subject. The readings can also challenge members to think about how their work can have tangible value. The charm and the threat of these questions lies in the uncertainties as to the kinds of answers that will attract substantial support in the coming years. This list is neither comprehensive or definitive. We will appreciate any suggestions about our choices and welcome new material. The asterisks indicate volumes which the compilers found especially suitable as painless introductions to our subject matter.

2. HISTORIC NOTES

"... reminder to a new generation of scientists that government policy toward them and toward their research careers must be viewed in context and that the context is hardly straightforward and rarely fully rational." (“Science” review of Ref. 2-4, below)

In the years before WWII, support for physics and budding physicists was very limited. Biographies and autobiographies of pre-war physicists provide revealing views of the physics community before WWII. Chapter 4 of Peter Galison's new

1. Peter Galison, "Image and Logic," (Chicago, IL, University of Chicago Press, 1997)

describes how physics at Harvard, Princeton, Berkeley, Stanford, Wisconsin, and MIT changed from before WWII to after it.

In the years following WWII, new patterns for the support of R&D in the US were created. The science policy that was created after 1945 was a political solution to a novel set of challenges. This solution involved many conflicting assumptions and difficult compromises. Descriptions of the human process by which post-war science policy in the US developed can be found in:

*1. Vannevar Bush, "Science--The Endless Frontier: A Report to the President on a Program for Postwar Scientific Research," (Washington DC, National Science Foundation, 1960). (This is not the original but a reprint with a historical introduction that will be of interest to many readers.) It is available on the web at www.physics.uiuc.edu/ysn/docs/html_articles/vbush1945.html.

*2. Daniel J. Kevles, "The Physicists" (Cambridge, MA, Harvard University Press, 1987).

3. Stuart Leslie, "The Cold War and American Science,"(New York, Columbia University Press, 1993).

4. Daniel Lee Kleinman, "Politics on The Endless Frontier," (Durham NC, Duke University Press,1995).

Writing readable history requires a narrative or analytic framework. Kevles' book is a highly regarded “history of a scientific community in modern America.” While it has a broad view of the physics community before WWII, from WWII on, it focuses on the high energy community as compared to for example, the solid state community. Leslie looks at the growth of electronics and physics research at MIT and Stanford in the post war

years in an "admirably researched, well documented, and well written," book. "An unspoken premise of Leslie's argument is that in the absence of military patronage, engineering and physics would have proceeded along a different route," but as a non-scientist, he "omits serious examination of what that course might have been." Kleinman's book provides a detailed view of process by which Bush's "Endless Frontier" recommendations evolved into the NSF. It ends on a discussion of recent controversies on US science policy that, in light of his historic narrative, suggests that some science policy problems never go away. Kleinman's work is "filtered through a large selection of political science writings" which non-political scientists may find difficult. Reviews of Leslie can be found in Science (260, 1161 (1993)) and Nature (363, 592 (1993)). Kleinman has been reviewed in Science (271, 156 (1996)), from which the quote at the start of this section was extracted.

3. THE NEW WORLD of the 1990s and BEYOND

It is generally accepted that the major factor in the high quality of American physics since WWII has been the level of support provided for physics research. Many physicists believe that the economic strength of the postwar years was based on the excellence of our academic research programs and that reduced support for academic physics will have dire economic consequences. The validity of this argument has been challenged by economists and policy analysts in the context of today's economy and by our current understanding of the role of research and development in developing the new products and processes which account for economic growth.

General discussions of the role of science and technology in generating economic growth in the modern US economy can be found in:

1. US Congress, Office of Technology Assessment,"Innovation and Commercialization of Emerging Technologies" (Washington DC, USGPO, 1995). (available at www.ota.nap.edu/pubs.html)

2. Council on Competitiveness, "Endless Frontier, Limited Resources - US R&D Policy for Competitiveness," (Washington DC, Council on Competitiveness, 1996) (available at nii.nist.gov/coc/coc_pubs.html).

A new textbook covering this subject with a European orientation is:

*3. Chris Freeman, and Luc Soete, "The Economics of Industrial Innovation, 3rd Edition," (Cambridge, MA, MIT Press, 1997).

This volume provides a broad historic overview of our subject. Of special interest is its detailed study the economic impact of many different technical innovations over several centuries. Many of the subjects discussed below are also covered in this textbook.

4. THE SCIENCE-TECHNOLOGY CONNECTION

Continuing study of the role of science and technology in commercial product and process innovation generates an evolving understanding of the contribution of research to economic growth. Understanding in this area traditionally occurs through complex case studies (data) and the creation of simple models (theory) which try to capture the lessons of these studies. The models inspire controversy both with respect to internal consistency and whether they describe reality. These controversies are important in our context because alternate models

provide different conceptual frameworks by which policy makers, scientists and engineers view the complex interaction between science, technology, and economic growth.

The contributions of science in winning WWII were celebrated in "Science--The Endless Frontier." Many of the innovations that occurred in the half of the twentieth century showed the limitations of the "uneducated, practical" inventor of American myth and the need for highly educated innovators capable of understanding and performing scientific and technical studies. These experiences produced a new model of innovation where technical progress began with basic research and "basic research is the pacemaker of technological improvement." Projects producing revolutionary technological innovations were theorized to move on a trajectory that began with basic research, passed through applied research, and ended in development. This so called "linear model" provided an appealing rationale for the support of basic research by the both the public and private sectors. It provided a vision which unfortunately many academic scientists still believe to be true. Its underlying assumptions had significant influences on R&D practices and policies in the US for many years after the end of WWII.

Today, the "linear" model has largely been abandoned. For example, the history of the support of "basic research" by federal agencies with well defined missions, where strategic choices between fields and areas of research were clearly made, has been cited to argue that the R&D activities of these agencies were not described by a "linear" model. Some these questions involve the interpretation of the phrase "without specific applications towards process or products in mind," found in the definition of "basic research." The ambiguity of the phrase "specific applications" allows ample grounds for differences of interpretation between program managers, lab-bench researchers, and policy analysts. In the 1970s and 80s, concern about US performance in the global economy spurred increased interest in the connections between scientific knowledge and economic growth and more fundamental reassessments of the "linear model". This led to support for more complicated models of the technological innovation process in the economic arena and the role of research in it. The following references provide two discussions of this subject.

1. The "linear" model, and an alternative, are summarized in Chapter 3 of the OTA report, "Innovation and Commercializaton of Emerging Technologies," cited above.

2. It is also discussed in a R&D Magazine Basic Research White Paper available on the web at www.rdmag.com/BRWP/index.htm.

These critiques draw on what are perceived to be unique features of today's economy. These include emphasis on time to market, extreme competitiveness, globalization of design, and manufacturing expertise, etc. The alternatives to the "linear" model all emphasize the importance of applied research, and strong, specific, feedback from users, customers etc. in driving technological innovation. The rapid, continuous evolution of products described by "Moore's Law" is seen as the major way in which research can contribute to economic growth.

A collection of essays:

3. Nathan Rosenberg, "Inside the Black Box: Technology and Economics,"(Cambridge, UK, Cambridge University Press, 1982),

include at least two short articles that provide useful background for readers not familiar with the academic study of science, technology and economic growth. These are "The Historiography of Technical Progress," beginning on p. 3., and "How exogenous is science," starting on p. 141.

It is interesting to consider how these modern views relate to earlier treatments of the value of investments in research, which some of us may have read in the Economics texts we used in college. These are still widely described in general texts on economics and summarized in:

4. F. M. Scherer, “Schumpeter and Plausible Capitalism,” IEEE Engineering Management Review, Spring 1994, p. 53.

5. CONTEMPORARY POLICY ISSUES

Some critics now argue that the necessary emphasis after WWII on the importance of basic research and the acceptance of the "linear" model by practitioners of R&D in the US in the post-war years led for some time to an over reliance on discipline-driven basic research as the prime instigator of technological innovation and economic growth. The "discipline" of the market economy has been portrayed as creating an environment where researchers need more "sophisticated" models of the innovation process. Two interesting examples of this, the first highly polemical and controversial, and the second more measured, are:

*1. Terence Kealey, "The Economic Laws of Scientific Research," St. Martin's Press (New York, 1996). A very brief summary is available at cato.org/dailys/4-11-97.html.

*2. Donald Stokes, "Pasteur's Quadrant: Basic Science and Technological Innovation, Brookings Institution Press (Washington, DC, 1997). A summary is available at www.wws.princeton.edu/programs/stpp.articles/dialog.html.

Kealey's (a biochemist) point of view has been widely discussed and condemned(Science 275, 750 (1997), Science and Government Report, February 15, 1997, pp. 4-5) and reviewed (Nature, 382, 123 (1996)). It was also reviewed in the September, 1997, issue of the newsletter of the Forum on Physics and Society of the APS. The Forum review drew a comment in the January, 1998, issue (available on line at www.aps.org). The Stokes book has been summarized in a recent Congressional Research Service report:

3. 97-836 SPR, Analysis of Ten Selected Science and Technology Policy Studies, which can be obtainedthrough the office of your congressperson. This is also available at: www.house.gov/science/L97-836.htm. (This report also summarizes many of the other issues covered in this bibliography.)

Two prominent industrial physicists have also recently commented in similar ways on the relationship of traditional research to the needs of industry today.

*4. John Armstrong (The Bridge, Summer, 1994, p11, Issues in Science and Technology, Summer, 1994, p19).

*5. Charles Duke (Physics World, August, 1997, p17).

Physicists who believe that the way we did things in the forty years since WWII was both good for physics and good for the nation would have to be able to refute the arguments presented in the first and last two references above. While Kealey represents an extreme point of view, Stokes, Armstrong, and Duke also call for major changes in the direction of physics research and education. All three suggest that practical goals, rather than

abstract disciplinary goals, are the most significant drivers of economicly significant technical innovations. All four critiques are framed within strong support for the value of R&D per se. As a result, for some physicists, these arguments may be a call for reform, rather than destroying the jewel in the post-WWII American crown.

6. ECONOMIC ANALYSES

Almost all of the arguments in the books and articles cited above are either anecdotal or qualitative. A satisfactory quantitative understanding of how research pays off in the marketplace could render most of the above irrelevent and unnecessary. Such a metric would allow the direct comparison of the returns on investments in research, and other instruments. For physicists who know the history of the transistor, the $100B per year of sales in the semiconductor industry would appear to be a splendid example of how research can have enormous economic payoffs, rendering this essay moot.

Detailed discussions and analysis of the current quantitative understanding of the economic benefits of research can be found in:

1. Nathan Rosenberg, Ralph Landau, and David C. Mowery, editors, "Technology and the Wealth of Nations," (Stanford CA, Stanford University Press, 1992).

2. Bruce L. R. Smith and Claude E. Barfield, editors, "Technology, R&D and the Economy," (Washington DC, Brookings Institution and American Enterprise Institute, 1996).

3. Jeffrey C. Fuhrer, and Jane Sneddon Little, editors, "Technology and Economic Growth," (Boston MA, Federal Reserve Bank of Boston, 1996).

The opening quote in this essay is from the volume by Smith and Barfield. It and our three references make it clear that, within the current methodologies of modern economics, no consensus exists as to a quantitative model of the contributions of scientific research to economic growth. In reading any of these works, physicists should remember that, "Economics is the study of how societies choose to use scarce productive resources that have alternative uses to produce commmodities of various kinds, and to distribute them amoung different groups." (P. Samuelson, and D. Nordhaus, "Economics," (McGraw-Hill, NY, 1989), p 12.) They should appreciate that just as biologists, chemists and engineers have good reasons for looking at the world in their particular ways, economists also have good reasons to focus on the behavior of markets and prices. There are non-economic forms of value. However, our interest here is in the relation of physics research to value as defined in economics.

The above volumes provide both a variety of points of view as well as critiques of the different points of view. Further readings can be found in a bibliography in Smith and Barfield, pg 173.

Physicists will probably be especially interested in the essays of the late E. S. Mansfield in references 1 and 2 above. “To learn about the excess social return to innovation, Mansfield et al. collected detailed information on a sample of innovations and calculated, for each one, the social and private return. The median social rate of return was over 50%....” This is one of the most widely cited results in the field. Like many popular quotes, it is often cited in misleading ways. Mansfield’s own words, and the critiques of his work in these two books, provide a spendid introduction to the complexities of this problem. For physicists who often have to worry about what is the right thing to measure, questions about what one can do with patent data, how to handle the human resources impact of physics research training etc., should strike a familiar note.

7. VALUATION OF R&D IN MODERN BUSINESSES

As difficult as it has proven to be to quantitiatively assess the economic contributions of past research to today's economy, it is even more daunting to look into the future and try to value today's research. This problem is closely related to the extensive literature on management of research in business. This field is also currently characterized by considerable debate. The dominant methodology of the past has been the calculation of the net present value (NPV) of a project (see references 1 and 2 below for detailed descriptions of this). This technique has been successfully applied to investment decisions such as the building factories and buying airliners, but has been widely criticized as a blunt tool more likely to provide the wrong answer than good guidance for R&D decision making (references 3-6 below).

The work of Black and Scholes, celebrated by the 1997 Nobel Prize in Economics, has been extended in the last decade to offer a different framework for this problem. The new approach stresses that current research investments provide information allowing for the better use of future investments. From this viewpoint, a research investment is analogous to a financial option. A company with an opportunity to invest in a project is holding something like a call option (reference 2 provides quantitative definitions of these terms). When the company makes this investment, it exercises its call option. The Black-Scholes formula values such options given certain assumptions and conditions. An interim research investment can be viewed as the cost of keeping such an option alive until the decision to go ahead with or cancel the project can be made with greater certainty about the outcome based on the results of the research. The value of this research then derives from the the asymmetry between the value of all the possible ways in which positive future returns could occur and the cost of pursuing the research until the option is exercised. Interestingly, in this methodology, the value of a research project increases with increasing future uncertainty. The ability to calculate the costs of deferring an investment in a project that depends on the results of research can increase the incentive for continuing the research.

There is extensive writing and debate on these subjects. An introduction to the financial practices of modern US business is provided by

1. Robert C. Higgins, "Analysis for Financial Management," 4th ed., Irwin 1995.

A richly quantitative discussion of valuation methods, with examples of applications to product development, can be found in Chapters 10, 20 and 21 of

2. R. A. Brealey, and S. C. Myers, "Principles of Corporate Finance," 5th ed., New York, McGraw Hill, 1996.

Some recent articles on strategies for investing in future businesses are:

*3. Avinash K. Dixit and Robert S. Pindyck, "The Options Approach to Capital Investment," Harvard Business Review, May-Jun 1995, p. 105.

*4. Hugh Courtney, Jane Kirkland, and Patrick Viguerie, "Strategy under Uncertainty," Harvard Business Review, Nov-Dec 1997, p. 67.

5. Terence W. Faulkner, "Applying 'Options Thinking' to R&D Valuation," Research/Technology Management, May-June 1996, page 50.

6. Graham Mitchell and William F. Hamilton, "Managing R&D as a

strategic option," Research/Technology Management, May/June 1988, p. 15,
and also IEEE Engineering Management Review 17, p.79 (June, 1989).

Reference 6 shows how the options and NPV approaches to R&D valuation apply to different types of R&D and argues that no single method adequately describes the returns on investment that the different types of research can provide.

A description of how Merck applies these ideas to planning its pharmaceutical research portfolios is in the January, 1994, editions of the Harvard Business Review. A related though different methodology is described in the March, 1998, issue of the same publication in an article about SmithKline Beecham. At the heart of such systematic approaches to investing in research is the assumption that research provides an option for a future investment of great strategic value to the company. To pursue this valuation strategy in the context of government supported scientific research requires two major steps. The first is that Science Policy provide the strategic direction against which the option value of a proposed research activity can be assessed quantitatively. The second is the definition of metrics to assess the impact of the strategic options.

8. USEFUL STATISTICAL INFORMATION

Understanding how research in general and physics research in particular can have an impact on economic growth in the US requires an appreciation of the magnitude of the US and world investment in R&D. Statistical information on the state of US Science and Technology can be found on line at:

1. National Science Board, "Science&Engineering Indicator-1998,"
(Washington DC, US GPO, 1998). (available on the web at
www.nsf.gov/sbc/srs/seind98/start.html)

2. R&D Magazine, "1997 Basic Research Survey," Cahner Publishing
Corp, January 15,1997, pg. 33. (available on the web at
www.rdmag.com/BRWP/index.html,
and in summary at www.battelle.org/pr/rd97.htm)
The 1998 edition has just appeared in the January issue of this magazine.

3. American Association for the Advancement of Science, Science Policy
Project at www.aaas.org/spp/dspp/rd/guide.htm.

4. John E. Jankowski, “R&D: Foundation for Innovation,”
Research-Technology Management, March, 1998, p. 14.

9. ANECDOTAL EVIDENCE and CONCLUSION

All physicists can look at the world around us and point to where physics has contributed to new products and industries. An example of this approach was the recent publication:

1. "The Physics of Materials-How Science Improves Our Lives," Committee
on Condensed-Matter Physics and Materials Physics of the Commission of
Physical Sciences, Mathematics, and Applications of the NRC (available at
www.nap.edu/readingroom/enter2.cgi?PS.html.).

The AIP is publishing a series of one-page summaries of the contributions of physics to a variety of technologies which are seen in everyday life.

2. Physics Success Stories. (available at www.aip.org/success/).

For many citizens, the anecdotal history of contemporary accomplishments is sufficient grounds for the support of physics.

Such support is a basic building block for a national consensus on the value of physics research. It does not, however, help the politician, bureaucrat, or policy maker who is trying to understand the additional benefits of a 7% annual increase in federal basic research funding as compared to, for example, a smaller annual increase in research funding and new tax credits for corporate R&D, or reduced corporate taxes, increased funding for Head Start, more Pell grants, etc. Even in an era of budget surpluses, choices like these will have to be made. A more thorough understanding of how different kinds of research and science education contribute to our modern economy, of how past R&D policies succeeded and failed, of how proposed policies will positively affect the US economy, and the development of metrics that allow the quantification of these contributions, would all carry weight in the debates over these choices. This would simplify the task of justifying to the political and corporate establishments support for what we as physicists think is worth doing.

For the present time however, physicists must be realistic about the kinds of arguments we can present. We can clearly point to where we have had great intellectual impact, but we must recognize that our economic impact has generally come as part of a community of scientists, engineers, and other technically interested individuals. If we work together with our professional colleagues, accept that many of the choices involved in the crafting of national science and technology policy are political choices, and are prepared to engage in the political process by which public policy choices are made, we now know enough about the economic impact of physics research and education today to feel comfortable, though not complacent, about the economic future of our profession.