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Discussion Paper:

AN ECONOMIC INVESTIGATION OF THE VALLEY OF DEATH IN THE INNOVATION SEQUENCE

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Discussion Paper:

An Economic Investigation of the Valley of Death in the Innovation Sequence

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EXECUTIVE SUMMARY

The Bush Administration's American Competitiveness Initiative has committed $50 billion over the next 10 years to fund technology research and $80 billion for technology R&D tax credits. Because of this sizable support and the important role that technology R&D plays in a country's economic growth, it is important to understand the linkage between government's support of technology R&D and the actual economic activity it generates.

The road between a discovery generated from basic research to a commercial product or process is long and, according to some, rife with significant roadblocks. Innovators and investors alike routinely claim that a "funding gap" or "Valley of Death" exists at an intermediate stage of this process, between basic research and commercialization of a new product. This intermediate stage funding gap may have a significant impact on the productivity of government-supported R&D efforts. In particular, if intermediate-stage financing is not available to individuals and firms that allow them to take a new innovation or discovery and transform it into a commercial product, then society should expect to see a diminished return on the public support of early stage R&D.

The United States Department of Commerce, Technology Administration is providing support to the Phoenix Center to conduct a one-year, three phase project to study the causes and potential solutions of the "Valley of Death" for technology development in the United States under Study Contract No. SB1341-05-2-0023 administered by KT Consulting, Inc. While several explanations for this Valley of Death have been proffered, this PAPER takes a decidedly different approach to this issue. We focus our attention on the notion that the Valley of Death is, in fact, a "valley" in the innovation process—an image that implies that funding for R&D projects is more readily available for "basic" or "early-stage" research (a "peak") than the intermediate stages (the "valley"). Our economic model indicates that such a nonlinear phenomenon can only occur if "noneconomic" investments (such as government expenditures on basic research) are made in very early stage research without sufficient attention to the likely investment decisions at later stages of the innovation process.

This is not meant to imply that government support of R&D activity is unwarranted; in fact, there are important and valid reasons for government to support R&D activity. In some respects, the Valley of Death may be an inevitable consequence of socially-valuable government intervention. An important question is whether technology policymakers should devote some attention and resources to the study of the optimal mix of government support for early-stage and intermediate-stage R&D projects. In particular, it may be possible to increase economic welfare from government R&D efforts by increasing support for intermediate stage projects or by altering the allocation of a fixed level of support between early and intermediate stages of the innovation process. Even if the current mix of funding across the stages of the innovation process is deemed optimal, it is also sensible to evaluate ways to increase technology innovation by assisting private investors in seeing projects through intermediate stages of the innovation sequence, which will bring innovations closer to commercialization and diffusion.

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I. Scope and Purpose of Project

The United States Department of Commerce, Technology Administration is providing support to the Phoenix Center to conduct a one-year, three phase project to study the causes and potential solutions of the "Valley of Death" for technology development in the United States under Study Contract No. SB1341-05-2-0023 administered by KT Consulting, Inc. This PAPER constitutes "Phase I" of the Project.[1]

Because of this sizable support and the important role that technology R&D plays in a country's economic competitiveness, it is important to understand the linkage between government's support of technology R&D and the actual economic activity it generates. The U.S. Government devotes significant resources to the support of basic technology research in the form of grants, tax credits, and other research and development (R&D) support. In the AMERICAN Competitiveness INITIATIVE, the Bush Administration has committed $50 billion over the next 10 years to funding technology research and an additional $80 billion in R&D tax credits.[2]

The United States is by no means alone in its direct and indirect support of research and development, and other countries have increased their direct support of research in the hope of improving their competitiveness in the global economy. According to data published by the OECD, since 2002, the United States' rate of growth in R&D spending averages 4% per year, a growth that is

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1 In Phase II of the Project, we will circulate this PAPER to interested persons for written comment and review. The Phoenix Center will then hold an interactive public "Summit" on the funding gap in the metropolitan Washington, DC area in Fall 2007 comprised of government officials, academics, senior executives, and other stakeholders. Persons interested in participating in this Summit should contact us via email at innovation@phoenix-center.org. In Phase III, we will incorporate the analysis set forth in this PAPER with a report of the Proceedings from the Summit into a Final Report that will be released in Fall 2007.

2 Office of Science and Technology Policy, Domestic Policy Counsel, AMERICAN COMPETITIVENESS INITIATIVE: LEADING THE WORLD IN INNOVATION (Feb. 2006) (available at: http://www.whitehouse.gov/stateoftheunion/2006/aci). In proposing to spend $50 billion over the next ten years on basic research and development, President George W. Bush said, "Federal investment in research and development has proved critical to keeping America's economy strong by generating knowledge and tools upon which new technologies are developed." *Id*.

"driven primarily by government expenditure."[3] Currently, the United States spends approximately 2.68% of its GDP per year on R&D, with roughly one-third (0.84%) of that coming from direct government expenditure.[4] Comparatively, the OECD reports that China has doubled its rate of R&D spending from 0.6% of GDP in 1994 to over 1.2% in 2005, an average growth rate of 20.4% compared to the United States' average growth rate of 4%.[5]

There is substantial support across the political spectrum, the academy and businesses for government investment in technology R&D. This support is based on persuasive research that shows that innovation drives economic growth and that the private sector will tend to underinvest in R&D, as the social value for innovation will outstrip the private value.[6] However, less attention is paid to the effectiveness of and impact from these government investments. Economic activity does *not* arise from basic research alone but from the later diffusion of new products, services or processes into the U.S. economy. As a result, understanding the roadblocks that may exist in the innovation process between basic research and commercialization—a process we call the "innovation sequence"—is important to understanding whether government investment in R&D is having its maximum possible impact on economic growth.

Research and experience shows such roadblocks exist in the innovation sequence. In particular, innovators and investors alike claim that at intermediate stages of the innovation sequence there is a "Valley of Death" where products or

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[3] HIGHLIGHTS, OECD SCIENCE, TECHNOLOGY AND INDUSTRY OUTLOOK 2006 (2006) (available at: http://www.oecd.org/dataoecd/39/19/37685541.pdf) ("OECD Highlights") at 2; *see also* National Science Foundation, FEDERAL FUNDS FOR RESEARCH AND DEVELOPMENT: FISCAL YEARS 2004-06, NSF 07-323 (June 2007) (showing growth rate of about 6% annually in nominal terms).

[4] OECD Highlights, *supra* n. 3, at 1-2.

[5] *Id.* at Figure 1.

[6] *See, e.g.*, Press Release of Sen. Edward M. Kennedy, *President Bush's Action on Global Competitiveness Needs to Catch Up with His Rhetoric*, (Apr. 19, 2006) (available at: http://kennedy.senate.gov/newsroom/press_release.cfm?id=52FF8F22-5F90-4A54-BACE-8C3C19BC4B6F) ("To compete and win in this global economy we must strengthen our federal commitment to basic research."); K. Hassett, *Innovation Drives U.S. Economy: R&D Drives Innovation*, SEMICONDUCTOR INDUSTRY ASSOCIATION NEWSLETTER, July 1, 2006 (available at: https://www.aei.org/publications/filter.all,pubID.24721/pub_detail.asp) ("Research and development activities often pave the way for other discoveries, but subsequent work is not always done by the initial pioneer. Thus, the return to society of R&D is likely significantly higher than the return to the individual doing the research….").

processes with welfare-enhancing potential perish for want of funding from either public or private sources. This Valley of Death may have a significant impact on the returns from public-supported R&D efforts. In particular, if intermediate-stage financing is *not* available to individuals and firms that allow them to take a new innovation or discovery and transform it into a commercial product, then government support of early stage basic research will not have the impact upon economic growth than it might otherwise have. While the Valley of Death is routinely discussed in industry and the academy, in this PAPER we analyze the nonlinear nature of the phenomenon and offer insights as to its causes and, at high level, potential solutions.

II. Analytical Overview

The purpose of this PAPER is simple: to provide policymakers an economic conceptualization and explanation of the Valley of Death. But we do not analyze this issue by discussing the conditions that explain why funding might be relatively scarce for certain types of R&D projects. Instead, we aim to understand why there is a "valley"—that is, why funding for basic research and late-stage commercialization R&D projects is more readily available while funding for R&D projects that stand between basic research and commercialization may be relatively scarce. Any explanation of the "Valley of Death" must explain why the "valley" is surrounded by "peaks."

In our view, our approach is valuable because it puts the plain policy focus on government's decision as to how to apportion its support for technology R&D—which has an important social value—between early-stage and intermediate-stage R&D projects. Government support for technology R&D is a valid and important social policy; however, government, entrepreneurs, researchers, and commentators should be aware that the mix of investments the government makes between early-stage basic research and intermediate-stage projects inevitably has an effect on the innovation process itself. Some effects may be intended (i.e., increased innovation), but some some (like a "Valley of Death") may not be intended. Our research shows that the Valley of Death, to a certain extent, could be considered a natural and expected by-product of the government support for basic research. Viewed in this way, a Valley of Death is not necessarily bad, but its emergence should counsel policymakers to strive to achieve an optimum mix between early and intermediate-stage funding in order to obtain the maximum economic output from government investment.

This PAPER provides an economic model of investment decisions in a multistage innovation process beginning with basic research and ending with commercialization. A "Valley of Death" implies that there are projects that emanate from basic research that are capable of generating socially-desirable commercial products, processes, or services but which are unable to obtain financing at the intermediate stage of the innovation sequence. Defining the Valley of Death in this way highlights the nonlinear nature of the "valley" that we are studying. Any explanation of the phenomenon must explain why a "valley" is present—that is, why funding for basic research is available to develop products or services that later are unable to obtain funding at the intermediate stages of the innovation sequence. This nonlinearity is the focus of our analysis.

A number of scholars have studied extensively the Valley of Death, particularly a series of informative and detailed studies by Auerswald and Branscomb (2002, 2003, and 2005).[7] Alternative characterizations of the Valley of Death have been proffered.[8] Regardless of how one labels this phenomenon, the

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[7] Significant contributions to the analysis of this issue include, but are not limited to, P. Auerswald and L. Branscomb, *Valleys of Death and Darwinian Seas: Financing the Invention to Innovation Transition in the United States*, 28 JOURNAL OF TECHNOLOGY TRANSFER 227 (2003); L. Branscomb and P. Auerswald, *Between Invention and Innovation: An Analysis of Funding for Early-Stage Technology Development*, Advanced Technology Program, National Institute for Standards and Technology (NIST), U.S. Department of Commerce Report, NIST GCR 02841 (Nov. 2002); P. Auerswald, L. Branscomb, N. Demos, and B. Min, *Understanding Private-Sector Decision Making for Early-stage Technology Development, A "Between Invention and Innovation Project" Report*, National Institute for Standards and Technology (NIST), U.S. Department of Commerce report, NIST GCR 02-841A (Sep. 2005); *see also* E. Williams, *Crossing the Valley of Death*, Warwick Ventures, University of Warwick (2004) (http://www2.warwick.ac.uk/services/ventures/valley.pdf); C. Wessner, *Driving Innovations Across the Valley of Death*, 48 RESEARCH TECHNOLOGY MANAGEMENT 9 (2005). The problem of funding in intermediate stages is not restricted to the United States. The Australian Institute for Commercialisation observes, "ideas from public research institutions are usually at a very early concept stage and therefore generally lack capital, channels to market, and often, clear market application or customers." Australian Institute for Commercialisation, *Driving Economic Growth by Improving Business Investment in R&D* (Jul. 2006) (available at: www.ausicom.com/04_newsletter/newsletter.asp?ID=110). The problem of funding in intermediate stages is not restricted to the United States. The Australian Institute for Commercialisation observes, "ideas from public research institutions are usually at a very early concept stage and therefore generally lack capital, channels to market, and often, clear market application or customers." Australian Institute for Commercialisation, *Driving Economic Growth by Improving Business Investment in R&D* (Jul. 2006) (available at: www.ausicom.com/04_newsletter/newsletter.asp?ID=110).

[8] Some commentators have labeled the "Valley of Death" differently, calling it a "Darwinian Sea." *See* Auerswald and Branscomb (2003), *supra* n. 7 at 230 ("The imagery of the Valley of Death (which connotes Death Valley in Nevada, USA) suggests a barren territory when, in reality, between the stable shores of the S&T enterprise and the business and finance enterprise is a sea of life and death of business and technical ideas, of "big fish" and "little fish" contending,

(Footnote Continued. . . .)

evidence indicates that private sector investors, including venture capital firms, invest very little money in intermediate stage projects and prefer to fund later stage projects that are closer to commercialization.[9] Indeed, the notion of a Valley of Death is so pervasive in industry that the term appears somewhat matter-of-factly in the engineering and manufacturing literature.[10]

However, in many discussions, the analysis does not explain the nonlinear nature of this disjuncture in the innovation process that is implied by the phrase "Valley" of Death. Rather, explanations for the Valley of Death in the literature instead often focus on the standard set of problems with private sector investments in R&D such as risk, uncertainty, increasing returns, appropriability, and so forth. Those explanations date back to Arrow (1962) and explain why profit maximizing agents will collectively underinvest in research in general.[11] Our analysis below demonstrates that those explanations alone cannot explain why a "valley" would emerge in one (intermediate) area of the innovation

with survival going to the creative, the agile, the persistent. Thus, we propose an alternative image: the 'Darwinian Sea.'").

9 Auerswald and Branscomb (2003), *supra* n. 7, report that only 4% of venture capital investments are at the intermediate stage of the innovations sequence. *See also* Z. Acs and F. Tarpley Jr., *The Angel Capital Electronic Network*, 22 JOURNAL OF BANKING & FINANCE 793 (1998) ("First, the investment focus of the venture capital industry has shifted progressively away from early stage towards later stage deals. Second, this shift in the investment focus has resulted in a widening of the equity gap as a result of a steady rise in the average size of investment. Third, there is a high degree of spatial concentration of venture capital activity, both in terms of firms and investments, in core regions at the expense of peripheral, economically lagging regions . . . Overall, there is not enough seed capital in the industry but too much later stage capital chasing few hot deals"); J. Lerner, *Angel Financing and Public Policy: An Overview*, 22 JOURNAL OF BANKING & FINANCE 773 (1998) ("Venture organizations are consequently unwilling to invest in very young firms that only require small capital infusions.").

10 *See, e.g.*, D. de Beer, G. Booysen, L. Barnard, and M. Trustcott, *Rapid Tooling in Support of Accelerated New Product Development*, 25 ASSEMBLY AUTOMATION 306 (2005) ("Many new products simply disappear in the product development valley of death, partly due to manufacturing costs and limited product development budgets"); *Web-based Guidelines Unveiled to Speed Innovations to Market*, 245 ENR 26 (2000) ("To ease the crossing of the Valley of death between technology innovation and commercialization, the Civil Engineering Research Foundation has developed draft guidelines …"); M. Lovell, *Trekking Through That Valley of Death--Sandia Technology,* INNOVATION: AMERICA'S JOURNAL OF TECHNOLOGY COMMERCIALIZATION (June/July 2005); *Entrepreneurs in the Valley of Death*, THE ENGINEER (Mar. 19, 1999); J. Morris, *Tech Transition Programs Bridging 'Valley of Death,' OSD Says*, 207 AEROSPACE DAILY 6 (2003).

11 K. Arrow, *Economic Welfare and the Allocation of Resources for Invention*, in THE RATE AND DIRECTION OF INVENTIVE ACTIVITY, pp. 609-25 (1962).

sequence. These conditions are necessary but not sufficient conditions for a Valley of Death. Stated simply, these earlier discussions do not explain why the Valley of Death is a "valley" in the innovation sequence and not simply an overall shortfall in investment in early-stage technology research. The image of a "valley" necessarily includes the presence of "high peaks" on both sides of the valley—an image that implies that the funding problems found at the intermediate stages of the innovation sequence are not present to the same degree in the early and later stages of the sequence. In fact, the explanations usually offered to explain funding difficulties in the Valley of Death are applicable to *all* stages of the innovation sequence and do not explain this nonlinear, "valley" characteristic.

Our economic analysis reveals that the presence of what we call "noneconomic activity" at early stages of the R&D process is required to create a "valley" at a later, intermediate stage of the innovation sequence. In essence, we demonstrate that the Valley of Death is really a product of noneconomic activity at the earliest stage of the process (basic research, which we call Stage 1 below). By "noneconomic activity" we mean that investments into early-stage basic research are not made solely by reference to the potential private gains that would emanate from that research. The government, which sponsors basic research for a host of reasons beyond the development of direct economic profit, is one possible noneconomic agent (but it is not the only one). Privately-funded research institutions and even researchers that pursue research for the sake of knowledge only and not economic gain can be the source of noneconomic activity. Moreover, for a variety of reasons, private firms may also be the unwitting source of noneconomic basic research activity.[12]

This insight is particularly important for technology policymakers. It is well-established that the private sector acting alone will tend to underinvest in R&D,

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[12] We label this activity "noneconomic" as a normative description and not in a pejorative way. Corporate R&D programs can suffer from agency problems that result on "noneconomic" research and development. For example, there may be vast differences between the motivations of the managers in basic research and those on the business side of the firm. S. Markham, *Moving Technologies from Lab to Market*, 45 RESEARCH TECHNOLOGY MANAGEMENT 31 (2002), at 32 ("Technical personnel … often do not understand the concerns of commercialization personnel … and vice versa. The cultural gap between these groups manifests itself in the results prized by one side and devalued by the other."). Firms may react to this risk by knowingly diversifying their R&D efforts, or as Richard Nelson described it, by "hav[ing] their fingers in many pies." R. R. Nelson, *The Simple Economics of Basic Scientific Research*, 49 JOURNAL OF POLITICAL ECONOMY 297 (1959) at 302. Such a strategy necessarily envisions that many research and development projects will fail.

and for this reason government (a "noneconomic entity" in our model) invests directly into certain R&D efforts. However, government activity is often limited to early stage research projects, which results in advances that the private sector is expected to commercialize. Our analysis suggests that the Valley of Death may be an inevitable consequence of government investment that is focused primarily on basic research for (at least) two reasons. First, this noneconomic activity creates a rift or a "valley" in the innovation sequence by inflating the output of basic research above what profit maximizing behavior is prepared to fund in later stages of the innovation sequence. Second, noneconomic activity in very early stages of the sequence may increase the cost of funds at intermediate stages by altering the "location" of lenders along the sequence. As a result, this noneconomic activity can increase the level of information asymmetry in the innovation process.

In many respects, it is unsurprising that the significant presence of an outside agent that is not maximizing profit (like the government) in the innovation process would results in some nonlinearity or disjuncture. Government support of basic research is justified by the inherent defects in the profit maximizing decisions for investments in technology research. Investment decisions that are driven by this social welfare mindset end when the government retreats from the process, and this leaves future decisions to the profit maximization criterion. Government support for R&D is based upon a judgment that social welfare gains of that investment spending surpass private welfare gains, so it may be that whenever government exits the process, a rift will occur. In this sense, a Valley of Death at or around the point where government investment ceases or fails tapers off will be, to a large extent, is inevitable.

That said, the fact that a Valley of Death may be a natural consequence of intervention is not a reason for complacency. In fact, it may be possible to increase economic welfare by expanding government support for intermediate stage projects or by altering the allocation of a fixed level of support between early and intermediate stages of the innovation process. It is likewise sensible to evaluate ways to increase technology innovation by assisting private investors in seeing projects through intermediate stages of the innovation sequence, which would bring new innovations closer to commercialization and diffusion.

The rest of this PAPER is organized as follows. In Section III, we provide a description of the innovation sequence, which serves as the environment in which investment decisions are analyzed. We explore the Valley of Death with particular attention to the recursive nature of the innovation sequence. Sections III and IV describe how such a "valley" would occur and reveals that traditional explanations for the Valley of Death do not necessarily explain the presence of a "valley" per se. We observe that the presence of noneconomic activity that provides funding for early stage basic research (such as the government) can create the conditions for the genesis of a Valley of Death. Section V explores this point further utilizing an investor location model which reveals that noneconomic activity in early stages of the innovation sequence affects the market decisions of investors and innovating entrepreneurs. In Section VI, we summarize our findings and provide suggestions for policy going forward.

III. A Valley of Death in the Innovation Sequence

The intermediate or "in between" nature of the Valley of Death requires that we evaluate R&D investments and innovation as a multistage process. We define that process as the "innovation sequence."

A. *The Innovation Sequence*

Many innovations can trace their roots to basic research, and much of this research is conducted with government support.[13] But by itself, basic research does not render final goods and services, but rather "results in general knowledge and an understanding of nature by its laws."[14] Ideas are the seeds of the innovation that manifests as goods and services and, in turn, drive economic growth and competitiveness.[15] Understanding how advances in basic research are effectively translated into economic growth, a sequence of events involving contributions from several players, from researchers to investors to customers, is critical to maximize the potential of the economy. In this paper, we describe the process that transforms ideas and discoveries into commercial production as the *innovation sequence*.

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13 Auerswald and Branscomb (2003), *supra* n. 7. An interesting case study of this fact in the context of the Valley of Death (though a slightly different version of it than we analyze) is provided in J. Golda and C. Philippi, *Managing New Technology Risk in the Supply Chain*, 11 INTEL TECHNOLOGY JOURNAL 95-104 (2007) (discussing the development of technologies resulting from the government's Strategic Defense Initiative program).

14 V. Bush, SCIENCE, THE ENDLESS FRONTIER. A REPORT TO THE PRESIDENT (1945), at 13.

15 As noted by Branscomb and Auerswald, "an invention is distinguished from an innovation by its character as pure knowledge. The direct products of a technological invention are not goods are services per se, but the recipes used to create the goods or services." Branscomb and Auerswald (2002), *supra* n. 7, at 28.

Thinking in terms of a sequence of steps is necessary when evaluating the Valley of Death. The Valley is alleged to occur at intermediate stages of the innovation process, where there is a "dearth of sources of funding for technology projects that no longer count as basic research but are not yet far enough along to form the basis for a business plan."[16] While considering innovation as a sequence is required for our analysis, the idea is certainly not original to this PAPER, nor is it particularly controversial.[17] In 1966, economist Robert Johnson states, "[i]nnovation is a time sequence occurring over an extended period," and divides this innovation sequence into four stages:

(1) The original idea or recognition of need for a product or improved process leading to research, perhaps resulting in an "invention." There may be application for a patent.

(2) An affirmative decision of technical and economic feasibility leads on to development work and prototype and trial production runs.

(3) With translation into commercial production—the initial 'point' innovation—the innovation process does not stop, but continues with improvements of the initial innovation and the spread of that innovation to other firms and industries ("imitation").

(4) The diffusion and improvement stage of innovation at the national level has a further stage as it spreads into international use.[18]

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[16] Auerswald and Branscomb (2003), *supra* n. 7, at 231-2.

[17] Auerswald and Branscomb (2003), *supra* n. 7, at 227 ("the process by which a technical idea of possible commercial value is converted into one or more commercially successful products"); FROM INVENTION TO INNOVATION, U.S. Department of Energy (1999).

[18] R. E. Johnson, *Technical Progress and Innovation*, 18 OXFORD ECONOMIC PAPERS, New Series 158 (1966), at 160-61. A similar description of the innovation sequence is found in B. Gold, *Technological Diffusion in Industry: Research Needs and Shortcomings*, 29 JOURNAL OF INDUSTRIAL ECONOMICS 247 (1981), at 256 ("… commercially important innovations are usually the outcome of a process involving: initial research budget allocations among alternative project possibilities; nourishing promising early developments with additional resources; transforming resulting laboratory processes or products into commercially available output through the design of various sizes and models of product and the construction or adaptation of suitable production facilities; and allocating additional resources to developing or adjusting marketing and distribution programs ").

While Stages 1 and 2 are essential ingredients to innovation, Johnson observes that the economy as a whole receives "[n]o benefit" until Stage 3 is reached.[19] In short, innovation only truly happens when the invention or discovery is converted into a consumable product, service, or process.[20]

Since we intend to analyze the Valley of Death which occurs at some intermediate stage of the innovation process, we conceptualize the innovation sequence in the three stages shown in Figure 1. These three stages comport closely with Johnson's description of the innovation sequence, and the three-stage model is a reasonable simplification of more complex versions of the innovation sequence.[21] The first stage, which we refer to as Stage 1, consists of basic research. The final stage, Stage 3, consists of the commercialization and diffusion of a new product or service. Much of the earlier research on the Valley of Death focuses upon the intermediate stage, or Stage 2, which generally consists of transforming a "discovery" or "idea" generated by basic Stage 1 research into a potentially marketable product or service.[22] We consider the sequence to move in one direction from early to later stages.

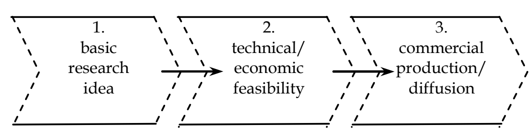

Figure 1. The Innovation Sequence

This depiction of the innovation sequence is, of course, a highly simplified abstraction from reality. Branscomb and Auerswald (2002, 2003) have described the process slightly differently, with five stages and feedback loops, but the approach shares the same general schematic as our simplified three-stage

19 Johnson (1966), *supra* n. 18, at 161.

20 It could be argued that information has value itself, irrespective of its commercial value.

21 *See* Auerswald and Branscomb (2003), *supra* n. 7.

22 Branscomb & Auerswald (2002), *supra* n. 7, at 32-41.

approach.[23] This three-stage approach lends itself readily to our analytical approach, without loss of generality.

Despite widespread acceptance that innovation is a process, the theoretical consequences of making investments in a multistage framework are typically ignored.[24] In some cases, discovery, innovation, and R&D are treated as an amorphous phenomenon; in others, particular stages are evaluated entirely separate from the others, ignoring the linkages between stages. In what follows, we take some initial steps at understanding how a Valley of Death may occur within an innovation sequence by formally considering these linkages between stages of the innovation process.

B. *The Valley of Death*

It is well-recognized that in general, without intervention, private industry will tend to underinvest in research and development activities. This argument was first set forward formally by Nobel Laureate economist Kenneth J. Arrow. In an influential paper, Arrow observed that "we expect a free enterprise system to underinvest in invention and research (as compared with an ideal) because it is risky, because the product can be appropriated only to a limited extent, and because of increasing returns in use. This underinvestment will be greater for more basic research."[25] Because private industry will tend to underinvest in

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[23] Auerswald and Branscomb (2003) divide the "innovation process" into five stages. *Supra* n. 7. The first stage is basic research which may lead to a technical concept of commercial value and, in some cases, a patent at Stage 2. In Stage 3, the new technology is "reduced to industrial practice," meaning the technology is developed to an extent that the supply- and demand-side potential of the technology can be assessed. Auerswald and Branscomb define Stage 3 as Early Stage Technology Development. In Phase 4, the earliest phase of commercialization begins with product development. After further market research, the technology reaches Stage 5 where a business is created to offer the technology to consumers as a product, service, or process. *See also* Branscomb & Auerswald (2002), *supra* n. 7, at 32-41.

[24] While the innovation process has been recognized as a series of steps (which do not necessarily occur in a linear fashion in all industries), the formal theoretical and empirical treatments of R&D to date typically avoid modeling innovation in this way, often treating R&D as synonymous with innovation. Yet, if one is concerned about the linkage between R&D expenditures and economic growth, then one must consider not only the amount of money spent on research but also whether the product of that research is converted into innovative products, services or processes.

[25] Arrow, *supra* n. 11. *See also* B. H. Hall, *The Financing of Innovation*, Working Paper (2005) for a review of current literature.

research, Arrow concluded that "for optimal resource allocation to invention it would be necessary for the government or some other agency not governed by profit-and-loss criteria to finance research and invention."[26] More or less, this rationale and has justified government spending and encouragement of basic research and development ever since. [27]

The shortcomings of profit maximization for research are not limited solely to basic research. Many commentators describe similar shortfalls in funding at intermediate stages of the innovations research where the research is more applied but still a long way from commercialization. According to some, the intermediate stage shortfalls are more dramatic than simply an underinvestment in research by profit maximizing agents. The shortfall, it is argued, creates a Valley of Death where "good lab discoveries go to die because they lack the funding necessary to become a commercial product."[28] Unlike Arrow's general argument about the deviation of private from socially optimal investments in research, this Valley of Death, according to Auerswald and Branscomb (2003), arises due to "a dearth of sources of funding for technology projects that no longer count as basic research but are not yet far enough along to form the basis for a business plan."[29] Clyde Frank et al. (1996) similarly describe the Valley of

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[26] Arrow, *supra* n. 11, at 20. *See also* S. Martin and J. T. Scott, *The Nature of Innovation Market Failure and the Design of Public Support for Private Innovation*, 29 RESEARCH POLICY 437, 438(2000) ("…the level of investment in research and development is likely to be too low, from a social point of view, whether market structure is nearly atomistic, a highly concentrated oligopoly, or something in between. Limited appropriability, financial market failure, external benefits to the production of knowledge, and other factors suggest that strict reliance on a market system will result in underinvestment in innovation, relative to the socially desirable level. This creates a prima facie case in favor of public intervention to promote innovative activity.").

[27] As Bronwyn H. Hall observes, Arrow's reasoning "is already widely used by policymakers to justify such interventions [into the innovation process] as the intellectual property system, government support of innovative activities, R&D tax incentives, and the encouragement of research partnerships of various kinds." Hall, *supra* n. 25, at 3. This view on the divergence between socially and privately optimal investment, and the remedial role of government, is widely, but not universally, accepted. For a critique of Arrow, *see* H. Demsetz, *Information and Efficiency: Another Viewpoint*, 12 JOURNAL OF LAW AND ECONOMICS 1-22 (1969).

[28] As one source describes it, this valley is "where good lab discoveries go to die because they lack the funding necessary to become a commercial product." J. Heller and C. Peterson, "*Valley of Death" in Nanotechnology Investing*, Foresight Nanotech Institute (available at: www.foresight.org/policy/brief8.html).

[29] Auerswald and Branscomb (2003), *supra* n. 7, at 231-2; *id.* at n. 17 ("The term 'gap' in this context connotes a disjuncture rather than a shortfall of resources").

Death as "the situation in which a technology … fails to reach the market because of an inability to advance from the technology's demonstration phase through the commercialization phase."[30]

Like underinvestment in research generally, the Valley of Death is often discussed as a shortfall in research funding due to risk, appropriability, and, in some cases, coordination problems at intermediate stages.[31] While these proffered explanations generally provide grounds for a shortfall in investments, they do *not* provide a precise explanation why one would observe a "valley" or disjuncture in the innovation sequence, and not simply underinvestment as a general phenomenon in early-stage research. The underinvestment incentives described by Arrow and others would apply to basic research projects as well as intermediate stage projects (if not more so), so the standard arguments for too little investment at intermediate stages are insufficient to explain the presence of a Valley of Death. A "valley" implies that there is "high ground" on either side, as illustrated in Figure 2.

Figure 2 is the dramatic portrayal of the "Valley of Death" that is now boilerplate for discussions of the Valley of Death.[32] It is apparent from the figure that to explain the presence of a "valley" one cannot simply rely upon general arguments that apply to the disincentive for private industry to invest in optimal levels of R&D generally, because those same incentives apply to more than just the intermediate stages of the innovation sequence. For there to be a "valley" in the innovation sequence, we must observe a shortfall of funding at an intermediate stage that is more systematic and profound than the shortfall to either side of the intermediate stage.

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30 C. Frank, C. Sink, L. Mynatt, R. Rogers, and A. Rappazzo, *Surviving the "Valley of Death": A Comparative Analysis*, 21 JOURNAL OF TECHNOLOGY TRANSFER 61-69 (1996).

31 Auerswald and Branscomb (2003) attribute the Valley of Death, in part, to "serious inadequacies in the information available to both entrepreneurs and investors." Auerswald and Branscomb (2003), *supra* n. 7, at 231.

32 The figure is attributed to House Science Committee Vice Chairman Rep. Vernon Ehlers (who has a Ph.D. in physics) was a co-author of the report, UNLOCKING OUR FUTURE: TOWARD A NEW NATIONAL SCIENCE POLICY, Committee on Science, U.S. House of Representatives, 105th Congress (Sep. 1998) (available at: http://www.access.gpo.gov/congress/house/science/cp105-b/science105b.pdf) at 39-46. Figure 2 is reproduced from Branscomb and Auerswald (2002), *supra* n. 7, at 36.

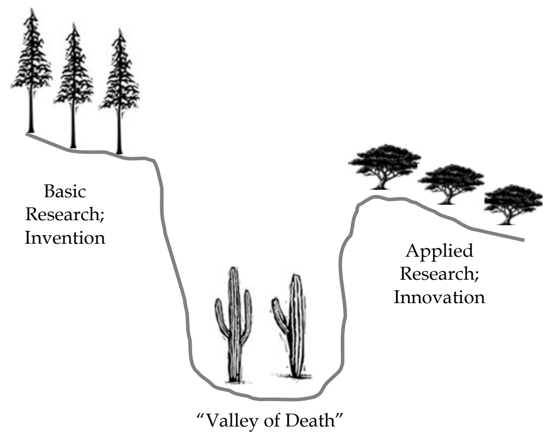

Figure 2. The Valley of Death Image

What is interesting about the Valley of Death is not only understanding the difficulty of obtaining funding for intermediate stage projects but also to understand why such difficulties are not as apparent for basic stage research, or how such problems are overcome. This is a different approach from most of the literature on this topic, which tends to discuss the Valley of Death by narrowly focusing on the traditional investment problems at the intermediate stage where it manifests. While risk, uncertainty, spillovers, and increasing returns to scale are certainly present at these intermediate stages and a necessary component for a Valley of Death to arise, those factors alone cannot explain the presence of a "valley" in the innovation sequence. In the following Sections, we present an economic framework that, in our view, begins to explain how such a phenomenon can occur and provides some insights as to possible solutions. Our analysis suggests that to a large extent the Valley of Death is created at Stage 1 and merely manifests at Stage 2.

IV. Investment Decisions in the Innovation Sequence

As we discuss above, for there to be a Valley of Death at an intermediate stage of the innovation sequence, there must be higher ground to either side. Stated simply, a valley will occur if both early and late stage projects are more frequently funded than those at intermediate stages. In this Section, we present a simple economic model of investment in a three-stage innovation sequence in order to help explain this phenomenon.

Say there is an entrepreneur that has a potential project that, if successful, has a fixed value V. To obtain this value, the entrepreneur must obtain financing at three different stages of the sequence (which we model as three separate investments, I_1, I_2, and I_3). Presumably, the investment amounts are sized $I_3 > I_2 > I_1$, in general.[33] In our model, the entrepreneur "borrows" those investments at a cost of $(1 + r)$ per dollar of investment, where r is the interest rate.[34] At each stage the sequence the research will either (i) show promise and move you to the next stage; or (ii) show failure, terminating the project. The probability of success at stage i is P_i (where i = 1, 2, or 3). We assume the entrepreneur participates in all three stages of the innovation sequence and acquires funding from a single investor. Investors operate in a competitive market. This setup is a simplification, but our general findings should hold in more complex settings.

If the project is expected to have no commercial value, then the investor will not initiate the project; all value is derived at the end of the sequence with the commercialization of the product or process. Thus, to determine whether or not the entrepreneur will proceed with the project we must solve the problem backward from Stage 3, the final stage of the innovation sequence.[35] The entrepreneur will "borrow" the required funds at Stage 3 if and only if

$$P_3(V - I_3(1 + r_3)) + (1 - P_3)(-I_3(1 + r_3) > 0 \qquad (1)$$

where Expression (1) is simply the probability-weighted payoffs of the project; the entrepreneur makes V - $I_3(1 + r_3)$ with probability P3 and loses $I_3(1 + r_3)$ with probability (1 - P_3). The entrepreneur undertakes the project only when the expected payoff is positive. We can also write Expression (1) as

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33 This relationship need not always be true, and variation among the sizes of investments presents opportunities for empirical tests of the Valley of Death.

34 Normally, we think of interest rates in the small percentages. According to the Dept. of Energy, however, for earlier stage research projects, "A standard, or baseline expectation, is found in the 10/5 rule that says you can expect a venture capitalist to want at least a 10 times return on investment within 5 years (at 14)."). This amounts to about a 60% annual return. *See also* M. Warnock, *Building a Fundraising Toolbox*, DIGITAL IQ (June 2005).

35 Alternative models of sequential investments in a much more complex setting include, *e.g.,* S. Bhattacharya, K. Chatterjee, and L. Samuelson, *Sequential Research and the Adoption of Innovations*, 38 OXFORD ECONOMIC PAPERS, SUPPLEMENT: STRATEGIC BEHAVIOUR AND INDUSTRIAL COMPETITION 219 (1986).

$$V > \frac{I_3(1+r_3)}{P_3}. \tag{2}$$

The left-hand side is the "benefit" and the right-hand side of Expression (2) the cost of the project. We note that the value V is a *private* value, so it excludes a portion of the social gain from the innovation that cannot be captured by the entrepreneur.[36] The comparative statics are intuitive. As the cost of the project rises (an increase in I_3 or r_3), the condition becomes more difficult to satisfy. All other things being equal, as the probability of success falls (P_3), the larger must be the value of the project V for the investment to be financially sound. As V rises, the condition becomes easier to satisfy, ceteris paribus.

Stage 3 products and processes do not appear out of thin air, however. In our model, the entrepreneur can only make a decision at Stage 3 if a project has been successfully funded at Stage 2 and Stage 1 of the sequence. Stepping back to Stage 2, the entrepreneur will undertake the second stage project costing I_2 if

$$V > \frac{I_3(1+r_3)}{P_3} + \frac{I_2(1+r_2)}{P_2 P_3}. \tag{3}$$

Notice that the decision to proceed at Stage 2 depends on the entrepreneur's decisions at Stage 3; the first term on the right-hand side of Expression (3) is the right-hand side of Expression (2). This dependence is rational—an entrepreneur would only seek to obtain second-stage funding if the project was worth pursuing in Stage 3.[37] An entrepreneur would not pursue the development of a rubber frying pan since there is no commercial prospect for such a technology.

A similar decision is made by the entrepreneur at Stage 1, where basic research occurs. Moving back to Stage 1, the entrepreneur commences the first stage project if

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36 Obviously, the less of the social value is captured, the less likely this condition is satisfied. This is the appropriability or spillover problem.

37 As one Angel investor stated: "We often ask our [Venture Capital] members to react to an investment we're considering. We want to be sure it might be attractive for future [Venture Capital] funding. If it is not; we'll decline." T. Stanco and U. Akah, Survey: *The Relationship between Angels and Venture Capitalists in the Venture Industry*, unpublished manuscript (2005) (available at: www.Lap2IPO.org).

$$V > \frac{I_3(1+r_3)}{P_3} + \frac{I_2(1+r_2)}{P_2 P_3} + \frac{I_1(1+r_1)}{P_1 P_2 P_3}. \tag{4}$$

Again, investment at Stage 1 is made only if the entrepreneur believes that investment at all subsequent stages is rational if the Stage 1 basic research has a successful outcome. The right-hand side of Expression (4) is the full expected cost of the project from basic research to the store shelf. The value of the project *V*, realized only after Stage 3 is complete, must exceed this cost in order for the project to be initiated by the entrepreneur.

As shown in Expression (4), the decision to invest at Stage *i* depends on the decision to invest at Stage *i* + 1 and all other subsequent stages.[38] In other words, the model is *recursive*, implying that if the investment yields good news at stage *i*, the project will be undertaken only if the entrepreneur is willing to invest again at *i* + 1 (and so forth). So, the decision to initiate a project is dependent on the relationship between the value of the investment *V* and the relevant cost components (*I*, *r*, and *P*) at each and every stage of the innovation sequence.

The recursive nature of investments in an innovation sequence is an important concept for understanding the Valley of Death. In essence, the interdependence of the investment decisions across the sequence implies phenomena occurring at intermediate stages cannot be evaluated independent of the other stages. It may very well be, and we argue it is so, that the "cause" of a Valley of Death rests at Stage 1 and not at Stage 2, even though the manifestation of it is at Stage 2. Riskiness, uncertainty, appropriability, increasing returns, and so forth at Stage 2 are essential ingredients for a Valley of Death, but they alone are not sufficient to create a Valley of Death. The Valley of Death is created by activity that occurs at Stage 1, but it becomes manifest at Stage 2.

A. *The Emergence of a Valley of Death*

Evaluating rational investment decisions in an innovation sequence reveals that a Valley of Death cannot emerge if only rational economic actors operate on profit maximization. To demonstrate, let us assume for sake of argument that

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38 It is easy to generalize the model to *N* stages. With *n* stages (*n* = 1, 2, … *N*) and investments $I_1, I_2, \ldots I_N$, and interest rates $r_1, r_2, \ldots r_N$, then $V > \sum_{i=1}^{N}\left((I_i(1+r_i)) / \prod_{j=n+1-i}^{N} P_j) \right)$.

"something" operates to increase the riskiness of Stage 2 projects and Stage 2 projects only. This Valley of Death is often discussed in such terms. In this situation, we would see the cost of funds r_2 increase while r_1 and r_3 remain the same. The higher cost of funds at Stage 2 naturally reduces the incentive to invest at Stage 2, but this reduction in investments at Stage 2 would *not* cause there to be a Valley of Death. A Valley does not appear because the higher cost of funds at Stage 2 (r_2) would be taken into account in the decision as to whether or not to invest at Stage 1 (as shown in Expression 4). If r_2 is high enough to block investment at Stage 2, then investment at Stage 1 will not occur. In other words, a structural problem that causes a shortfall in funding (a funding gap) at Stage 2 would have an impact on earlier stages of the innovation sequence which precludes the manifestation of a Valley of Death. This simple and intuitive result is perhaps the most important contribution of this Project.

The recursive nature of an innovation sequence implies that for a Valley of Death to exist at an intermediate stage, *noneconomic activity* must be present at earlier stages. By noneconomic activity we mean investments in Stage 1 projects by entities that are not taking into account what happens in later stages of the sequence. If later stage decisions are a part of earlier stage decisions, which is consistent with profit maximization, then a Valley of Death of any significance cannot emerge. Put simply, the Valley of Death arises when there is more output at Stage 1 than the private sector is willing to fund at Stage 2. For this to occur, the recursive nature of the investment calculus is being ignored at Stage 1.

This noneconomic activity can and does take a number of forms. Examples include government spending on basic science projects undertaken solely for the sake of knowledge or at the full discretion of the researcher uninterested in commercial prospects, by an individual inventor that who maxes out his credit cards researching a technology that has no hope of commercialization in his lifetime, spending by universities on research that is directed more at driving alumni donations or student enrollment than on inventing new products, and research by corporations outside of their immediate field of expertise or that suffer from internal principal-agent problems between the research and business segments.[39] There are, of course, many other ways in which noneconomic activity may occur at Stage 1.[40]

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[39] This type principal-agent problem occurs frequently in business organizations. *See, e.g.*, A. A. Alchian and H. Demsetz, *Production, Information Costs, and Economic Organization*, 62 AMERICAN ECONOMIC REVIEW 777-795 (1972); J. E. Stiglitz, PRINCIPAL AND AGENT, IN THE NEW

(Footnote Continued. . . .)

We note that this "noneconomic activity" is not necessarily unwise or inappropriate, and we imply no pejorative connotation to the term. In fact, government support of basic research efforts, according to Arrow and others, is necessary since relying solely upon private profit motive for R&D arguably will not achieve optimal outcomes. Indeed, the majority opinion is that the government has an important and necessary role to play in R&D, primarily due to spillovers and risk inherent to early stage research. It should be understood, however, that government intervention has both intended and unintended consequences; it may be necessary to take the bad with the good. Support of basic research increase innovation, but also can result in a Valley of Death. Possibly policy responses to the Valley of Death are something we discuss later in the PAPER.

B. *Numerical Example*

Using Expression (4), we can demonstrate how noneconomic activity creates a Valley of Death using a numerical example. For the purposes of this demonstration, we assume there are 1,000 potential projects, and we assign values for the required investment (I) and the probability of success (P) for each stage of each project. Each project has a private value V and a social value V_S (we allow spillovers in the example), where $V < V_S$. We assume $I_3 > I_2 > I_1$ and that $P_3 > P_2 > P_1$.[41] This simple example is illustrative of our economic model only and the results are not intended to reflect real world outcomes.

PALGRAVE: A DICTIONARY OF ECONOMICS, VOL. 3, pp. 966-71; O.E. Williamson, MARKETS AND HIERARCHIES: ANALYSIS AND ANTITRUST IMPLICATIONS (1975).

40 Another potential source of noneconomic activity arises simply from the fact that basic research is full of surprises and often has a portfolio nature to it. Many of the greatest discoveries were accidents, such as Post-It notes, which were made possible by a failed attempt to make super strong glue and instead making a super weak one. *See* http://www.ideafinder.com/history/inventions/postit.htm. In other words, a rational economic actor may undertake a project that produces byproducts from basic research. If these byproducts are not deemed useful by the entrepreneur, they may not be funded in later stages. Investments in the innovation sequence are motivated by expectations, not accidents, so the logic of recursion is intact.

41 All inputs are drawn from the Chi-square distribution. Investment levels at each stage are Chi-square with 5, 10, and 50 degrees of freedom. Probability levels are Chi-square with 5, 30, and 200 degrees of freedom, with this output divided by the largest value of each to constrain the probability to the unit interval. Social value is drawn from a Chi-square distribution with 3 degrees of freedom, with this output multiplied by 300. Private value is λ of social value, with λ

(Footnote Continued. . . .)

Table 1 summarizes the output of the numerical example. First, the table summarizes the projects undertaken given the maximization of social welfare by a social planner. In this case, the cost of the project is compared to social value (V_S) rather than private value V. Based on Expression (4) and the randomly generated inputs, the social planner undertakes 834 of the 1,000 potential projects. Of these, 53 projects successfully navigate the innovation sequence to become "Innovations."

Next, we summarize the project undertaken given rational economic agents motivated by profit maximization. Now, only 342 projects are undertaken at Stage 1, resulting in 27 Innovations. As expected, profit maximization in the presence of spillovers leads to an underinvestment in research from a social perspective and lower social welfare. Third, we inflate r_2 in Expression (4) so that the incentive to invest at Stage 2 is diminished for all projects. In other words, we introduce a high level of risk unique to Stage 2, a common explanation for the Valley of Death. While the number of projects falls at Stage 2 (from 81 to 78), investment in projects also falls at Stage 1 (from 342 to 327).

Table 1. Numerical Example of Valley of Death

	Funded Projects			
	Stage 1	Stage 2	Stage 3	Innovations
Social Welfare Max	834	164	72	53
Profit Max	342	81	38	27
Profit Max with risk premium at Stage 2	327	78	36	25
Profit Max with Noneconomic Activity	834	118	52	38
	Probability of Funding for a Socially Beneficial Project			
	Stage 1	Stage 2	Stage 3	
Social Welfare Max	100%	100%	100%	
Profit Max	41%	100%	100%	
Profit Max with risk premium at Stage 2	39%	100%	100%	
Profit Max with Noneconomic Activity	100%	72%	100%	

Finally, we introduce noneconomic activity at Stage 1 by allowing a noneconomic agent to fund all socially-beneficial projects at Stage 1. In all subsequent stages, however, investment decisions are made by private, profit maximizing agents. Again, we have 834 Stage 1 projects, all of which are socially desirable. The profit maximizing agents at Stage 2, fund 118 of these projects.

drawn from a Chi-square distribution with 5 degrees of freedom, the output of which is divided by the largest value to constrain λ to the unit interval. A project is successful if the probability P is greater than U, where U is drawn from a uniform distribution.

So, the noneconomic activity at Stage 1 increases the number of Stage 2 projects relative to the profit maximization case (from 81 to 118), and there are more Innovations (from 38 to 52). This example illustrates the logic of government funding of basic research.

We turn now to the Valley of Death, which we define to be the inability of socially-beneficial projects to acquire funding at Stage 2. (By socially-beneficial, we mean a project that would funded by a planner that seeks to maximize social welfare.) In the lower part of Table 1, we provide the probabilities that a socially-beneficial project is funded at each stage given success at the previous stage. The social planner funds all socially beneficial projects, so in the first row all projects are funded with 100% probability. Profit maximizers, however, underinvest in basic research, funding only 41% of socially desirable projects at Stage 1. However, the decision to fund the project at Stage 1 implies a commitment to see the project through as long as the research proves successful. After Stage 1, then, the profit maximizing agent funds 100% of socially-beneficial successes from the prior stage. Spillovers, then, do not create a Valley of Death.

When we add the risk premium to funding at Stage 2, we saw a reduction in the number of Stage 1 project initiated by the profit maximizing agent. From the table, we see that only 39% of socially-desirable projects are initiated at Stage 1. However, all successes at Stage 1 are funded in Stage 2 and 3. Therefore, there is no Valley of Death. Thus, in addition to spillovers, the riskiness of investments at Stage 2 also does not create a Valley of Death.

In our final case, we introduce noneconomic activity at Stage 1. The table shows that 100% of socially-desirable projects are funded at Stage 1. However, when profit maximization takes over at Stage 2, only 72% of socially-desirable projects coming out of Stage 1 are funded. Of the successful Stage 2 projects, 100% are funded at Stage 3. Thus, it is clear from this numerical example that it is noneconomic activity that creates the Valley of Death when defined to be the failure of private investors to fund socially-desirable projects at Stage 2 (or Stage 3 for that matter).

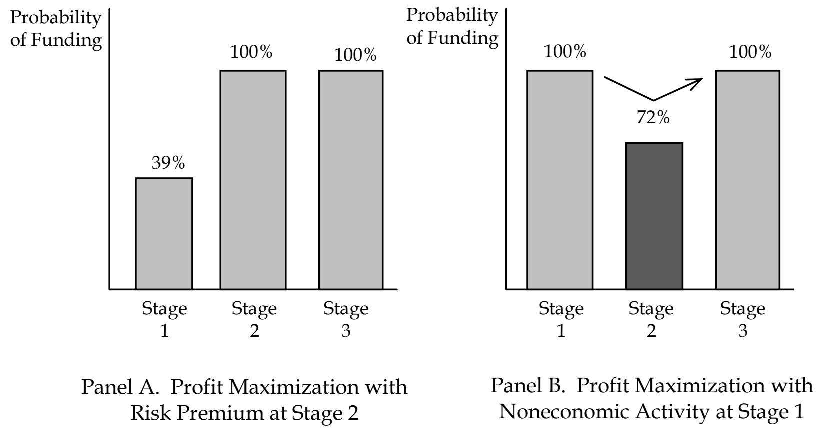

Figure 3. Noneconomic Activity and the Valley of Death

Figure 3 illustrates the difference between the last two scenarios (profit maximization with a risk premium at Stage 2 and profit maximization with noneconomic activity). While the risk premium at Stage 2 reduces Stage 1 investments, all successful Stage 1 projects that have a net social value are funded at Stage 2. In contrast, with noneconomic activity funding all projects with net social value at Stage 1, a Valley of Death manifests at Stage 2 when the investment decision changes from welfare maximization to profit maximization. Since the private sector will not initiate any project that will not be funded in later stages, all successful Stage 2 projects are funded even with noneconomic activity at Stage 1. The "valley" nature of the problem is clearly illustrated by this figure.

V. Information Asymmetry and a Gap in the Innovation Sequence

The discussion above reveals that a Valley of Death of any significance cannot occur in the presence of rational economic behavior in a free market. Further, things like riskiness and spillovers at Stage 2 cannot explain a Valley of Death, though they are an essential component of the Valley of Death and may cause an underinvestment in research generally. In our framework (an important qualification), the Valley of Death emerges only in the presence of noneconomic activity of some sort at Stage 1. Noneconomic activity creates a Valley of Death when such activity produces more Stage 1 output than the private sector is willing or able to handle at Stage 2 (where noneconomic behavior is presumed absent). In essence, the Valley of Death occurs at or around the meeting point of where a welfare-maximizing process fades and a private profit-maximizing process steps to the forefront. In our framework, this meeting point occurs at the junction of Stage 1 and Stage 2 of the innovation sequence. Given the dramatic differences between the outcomes of these two decision criteria, a rift occurs.

In this section, we describe how the noneconomic activity at Stage 1 may do more than simply inflate Stage 1 output thereby causing a Valley of Death by showing how this noneconomic activity at Stage 1 may exacerbate the valley by increasing the cost of funds at Stage 2. Our analysis is based on a model of lender specialization (or location) along the innovation sequence, where investors "locate" their expertise along the innovation sequence to fund a project. A principal argument in the underinvestment in R&D projects is the fact that investors as a class may not have sufficient information about the technological or commercial prospects for a particular type of innovation at earlier stages of the sequence (or that obtaining that level of expertise is too costly). If an investor has little knowledge about the project—i.e., the investor's location is in commercial rather than scientific expertise—then the investor will demand a high premium on it's funding. The greater the distance between the location of the investor and the location of the project, the higher the risk premium. We show here that noneconomic activity may affect the location of lenders, possibly driving up premia for investments at intermediate stages of the innovation sequence.

A. *The Basic Economics of Information Asymmetry and Investment*

As described by Hubbard (1998), information asymmetries play an important role in investment decisions.[42] In deciding whether to make an investment, investors routinely take into account the chance that they may not fully understand the potential for success of a product or service. The less investors know, the higher the rate of return they will demand on a particular investment.

Figure 4 portrays the neoclassical demand for capital in a simple setting. The cost of capital is on the vertical and the quantity of capital is on the horizontal axes. The demand for capital is the curve labeled *D*. The law of demand applies so that as the cost of funds falls, the quantity demanded of capital rises (*D* is

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42 *See, generally,* R. G. Hubbard, *Capital-Market Imperfections and Investment*, 36 JOURNAL OF ECONOMIC LITERATURE 193 (1998). A number of simplifying assumptions are made for the analysis: (i) zero depreciation; (ii) zero taxes; (iii) zero cost of capital stock adjustments; (iv) a fully reversible investment; and (v) zero price of capital goods. *Id.* at 4, n. 3.

downward sloping).[43] In the neoclassical investment model, the supply of capital is horizontal at *r*, the risk-adjusted market (real) rate of interest. So, in the neoclassical model, the first-best capital stock is determined by the intersection of *D* and $\bar{r}$, which in the figure is at capital stock *K**. At *K**, the marginal profitability of capital equals the market interest rate.

As shown in Figure 4, in a simple setting without any information asymmetries and without a divergence in private and social benefits, the entrepreneur will view his cost of capital as the market interest rate $\bar{r}$. Consequently, the entrepreneur will select the first-best quantity of capital stock, *K**. In reality, however, the entrepreneur is likely to have higher quality information than outside investors will about the particular project in question.

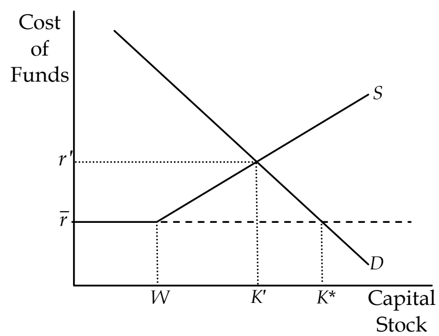

Figure 4. Asymmetric Information and Investment

This asymmetry in information has an impact on both the investor's decision to invest as well as the entrepreneur's decision to continue with the research project. For example, let us assume that the entrepreneur as an idea, derived

43 If the investment opportunities of the firm improve, then the demand curve will shift to the right. At a fixed *r*, the equilibrium capital stock will rise accordingly. In contrast, a reduction in the quality of investment opportunities, other things constant, will reduce the equilibrium capital stock. On the supply side, if the market rate of interest rises, investment opportunities constant, then the equilibrium capital stock will fall, and vice-versa for reductions in the interest rate. So, the comparative statics of the investment model are familiar and intuitive.

from her basic research, which is thought to have a net private value that exceeds what she is willing to invest in the project. She is willing to invest up to *W* of her own money in order to take the product to market. To take the product to market, the entrepreneur believes she needs to raise from investors additional capital *K* and some other inputs *Z* (i.e., intangible assets).[44] Since the entrepreneur invests *W*, the entrepreneur will seek the outside investment of *K* and *Z* so long as the cost of that outside investment is less than the value she expects to receive from the personal investment she has made in the project. Stated formally, the entrepreneur will initiate the project and seek outside financing only if the value of the project less payment to outside investments exceeds $(1 + \bar{r})W$.[45]

Now we consider the impact information asymmetries has upon this equation. Suppose that outside investors can only observe and understand the amount of capital *K* invested in the project; *Z* is known only by the entrepreneur. This information imperfection leaves open the possibility for the entrepreneur to divert funds to *Z* for personal enrichment (say, by investing at $\bar{r}$). Outside investors are not ignorant of this possibility, so the investors must be compensated for the risk that they have imperfect or incomplete information, which can be referred to as "information costs." Therefore, the contract between the entrepreneur and the outside investors must include some type of incentive constraint that makes the gain from honest action greater than from dishonest action.

As a consequence of the incentive constraint, the supply curve now has two components, as illustrated in Figure 3. The first, horizontal segment is the cost of internal funds *W*, which is equal to the market interest rate $\bar{r}$. There are no agency costs with the use of internal funds. After *W* is exhausted, however, the risk of opportunistic behavior on behalf of the entrepreneur increases the cost of funds since outside investors must be compensated for information costs. So, after *W* is spent and outside funds are required, the supply curve of capital funds (labeled *S*) is upward sloping, implying outside funds have a higher shadow price than internal funds. When information is expensive to obtain, the upward sloping portion of the supply curve is steeper.

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44 This infusion of capital is expected to produce a positive expected output, so that output rises with the use of the capital *Z*.

45 In other words, the entrepreneur's net worth has an opportunity cost equal to the market interest rate *r*.

In the presence of information costs, the equilibrium capital stock is determined by the intersection of *D* and *S*, which in this case is at capital stock *K*'. Obviously, this capital stock is less than the first-best quantity *K**, so the information costs lead to underinvestment by the entrepreneur (relative to a zero information cost alternative). In this case, there is a shortfall of capital equal to *K** - *K*' that arises from information asymmetry.[46] Thus, actions that increase information asymmetries increase the cost of funds and thereby reduce investments, and we employ this intuition in our lender location model in the next section.

B. *A Model of Investor Location*

Most skeptics of the notion of a Valley of Death suggest that the large and growing Venture Capital industry, which specializes in high risk ventures, is sufficient to eliminate any inefficiency in the intermediate stages of the innovation process. In response, numerous researchers and Venture Capitalist themselves point to the fact that Venture Capital firms have, over time, increasingly focused their efforts on larger sized, later stage projects.[47] Thus, Venture Capital funds are rarely available (at least at a reasonable cost) for intermediate stage projects.

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[46] This simple logic has served as the foundation for a number of empirical tests on the role of information imperfection and investment. A number of empirical studies on the topic consider whether or not firms invest differently when some portion of their capital spending can be financed out of internal funds (*i.e.,* cash flow). The basic premise of this empirical research is that due to information imperfections (moral hazard and adverse selection), there exists a divergence in cost between using internal (*e.g.,* cash flow) and external sources (*e.g.,* creditors) of funds. For an analysis of the role of internal financing on R&D expenditures, *see, e.g.,* C. Himmelberg and B. Peterson, *R&D and Internal Finance: A Panel Study of Small Firms in High-Tech Industries*, 76 REVIEW OF ECONOMICS AND STATISTICS 38-51 (1994); B. Hall, J. Mairesse, L. Branstetter, and B. Crepon, *Does Cash Flow Cause Investment and R& D: An Exploration Using Panel Data for French, Japanese, and United States Scientific Firms*, ECONOMICS WORKING PAPERS 98-260, University of California at Berkeley (1998). Much of the literature is reviewed in Hall, *supra* n. 25.

[47] *See, e.g.,* J. Lerner (1998), *supra* n. 9; Acs and Tarpley (1998), *supra* n. 9; Stanco and Akah, supra n. 37; T. Hellmann and M. Puri, *On the Fundamental Role of Venture Capital*, ECONOMIC REVIEW: FEDERAL RESERVE BANK OF ATLANTA, 4Q (2002), at 23 ("the changes in the competitive landscape [of venture capital] affected the more experienced venture capitalists. Venture capitalists that before would have raised a fund of, say, $50 million were now able to raise $500 million and still obtain their 2 percent management fee. With a lot more money for every partner to invest, many experienced venture capitalists changed their business model. They invested in many more companies and tried to place larger sums of money into their portfolio companies, and many venture capitalists moved toward later-stage investing.").

In this section, we focus on lender location along the innovation sequence and how it impacts information asymmetries. By "location" we essentially consider the ability of investors to specialize or develop expertise in a particular area. As a result, investor "location" encapsulates a number of factors, such as a decision by a venture capital firm to hire medical doctors in order to foster a specialization in biotechnology or an Angel investor that only invests in companies within a day's drive of his home.

Our analysis suggests that the presence of noneconomic activity at Stage 1 can alter the location of lenders and thus the cost of funds at intermediate stages of the innovation sequence. The movement of Venture Capital firms toward later stage projects is also explained by the model as a response not only to noneconomic activity at Stage 1 but also the combination of small investment sizes and large due diligence costs of Stage 2 projects.

C. *The Role of Investor Specialization*

As we have described above, the cost of funds for an investment project depends on information the investor has about the activities it is asked to support. Information asymmetries can arise when investors, such as Venture Capital funds, do not specialize or "locate" their investment activities near the intermediate stage of the innovation sequence. The distance between the investor and the project causes a risk premium, thereby reducing investment in intermediate stage projects. We turn now to the question of lender specialization along the innovation sequence and evaluate the impact of noneconomic activity on location.

As a preliminary matter, we note that it is beyond the scope of our analysis to provide a complete theory of the market structure of the financing industry or the innovation process. Rather, we present here a simplified scenario that highlights the basic idea of investor location. In our construct, an "average" or "typical" project seeks financing from an investor located at the single spot in the innovation sequence that minimizes the expected costs of funding a project, given the probabilities of success along the various stages. (We consider multiple investor locations briefly *infra*.) This approach is, at best, a first approximation given (1) a competitive financing industry, so prices equal average costs; and given (2) that there are sunk costs both to the financing relationship (so the investor must pay a sunk cost to become acquainted with a project, at whatever stage) and sunk costs to each location choice.[48] In other words, there is due diligence that is project specific, an assumption that is not controversial.

Say the activities at each stage of the innovation sequence have characteristics given by a random variable θ with $\theta \sim (0, \sigma^2)$. A investor d distance away from the specific project does not see θ, but instead sees a signal of θ equal to $s = \theta + d\varepsilon$, where $\varepsilon \sim (0, \sigma_\varepsilon^2)$. So, the investor's signal—his ability to judge and assess the risks and benefits of the project—gets worse as he gets "further away" from the project.[49] This poor signal, in turn, increases his costs of monitoring or otherwise managing the investment.[50] In other words, investors specializing in commercial projects are unlikely to have expertise in the vagaries of basic research, and researchers are rarely experts in, or even have an interest in, commercial ventures.[51]

Consider an investor that wishes to minimize the cost of funding a typical project. The investor does so by choosing some point ℓ in the innovation sequence that minimizes the cost of funding the project, so that the investor can offer the lowest cost of funds to the entrepreneur. For convenience, assume that all the locations in the innovation sequence are distributed across the unit interval, so $0 \leq \ell \leq 1$. For any given location, there is an information premium

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48 Sunk costs are fixed costs that once incurred have no opportunity cost (they cannot be recovered). A non-refundable deposit is a sunk costs, in that even if plans change, the money cannot be recovered. Investments in due diligence that are project specific are sunk. If some of the knowledge obtained during due diligence is transferable to later projects, then the cost of that knowledge is not sunk.

49 A suitable analogy to this setup is transport. In economic models of transport, the cost of an item is higher the further away the customer is from the item's initial location due to transport costs. *See, e.g.,* J. Tirole, THE THEORY OF INDUSTRIAL ORGANIZATION (1995) at ch. 7.

50 By "distance" we do not mean physical distance, but distance is used in an information context. In some cases, physical distance may be meaningful indicator. Research shows, for example, that Angel investors typically invest only in projects that near to home or to their business networks. S. Prowse, *Angel Investors and the Market for Angel Investments*, 33 JOURNAL OF BANKING & FINANCE 785 (1998). It seems obvious that this "rule of thumb" is based on the quality of the information obtainable from geographic proximity to the project. We also recognize that there are conceptual differences in the costs of investing in an established firm in general as opposed to the cost of that firm deciding to invest in a particular research project.

51 Auerswald and Branscomb (2003), supra n. 7, at 230 ("Few scientists engaged in academic research (or the agencies funding their work) have the necessary incentives or motivation to undertake this phase of the reduction–to-practice research.").

attached to a loan made at another location. Let this premium on the cost of funds be equal to $k(d^2/2)$, where $k > 0$, for distance d from ℓ to the investment location. In this formulation, the premium is increasing and non-linear in distance.[52]

Figure 5 illustrates the basic setup with our three-stage innovation sequence. Stage 1, with investment I_1, is at location "0" and Stage 3, with investment I_3, is at location "1." Stage 2 is at some intermediate point; let x be the location of Stage 2 with investment I_2 (which could be at any point between Stage 1 and 3). The probability the research is successful at each stage of the sequence is P_1, P_2, and P_3. (In the simplest format, the P_i are also the frequencies of projects at each stage.) The project has investment I_1 for certain as it is the starting point. Investment I_2 occurs with probability P_1 (the success rate of Stage 1), and investment I_3 with probability $P_1 \cdot P_2$.

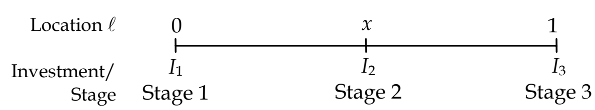

Figure 5. Lender Location

The investor seeks to minimize the cost to the entrepreneur of funding the entire project by locating at some point ℓ, where cost is

$$C = k\left[\frac{\ell^2}{2} I_1 + P_1 \frac{(x-\ell)^2}{2} I_2 + P_1 P_2 \frac{(1-\ell)^2}{2} I_3\right], \tag{5}$$

where cost is simply the premia multiplied by the probability-adjusted investment amounts. Costs (C) are minimized by choosing ℓ such that

$$\ell^* = \frac{xP_1 I_2 + P_1 P_2 I_3}{I_1 + P_1 I_2 + P_1 P_2 I_3}. \tag{6}$$

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52 If the premia increase linearly in distance, then we get corner solutions with locations at 0, 1, or x.

Inspection of Equation (6) renders a few interesting insights. Foremost, the relative size of the investments is an important determinant for investor location. Since the size of the investment often plays a role in discussions of the Valley of Death, it is important to have some understanding of why size matters. From Equation (6) we see that as I_3 becomes large relative to I_1 and I_2, the cost minimizing location ℓ^* moves toward 1. Since it is plausible, in many cases, that the commercialization stage will require the largest investment, this model indicates that investors are encouraged to locate closer to Stage 3 of the sequence.[53] By doing so, this drives up the cost of funds for (all) earlier stages of the innovation sequence, where the required investments are smaller. These investment amounts are, however, weighted by the probabilities of success from earlier stages of the sequence. Low probabilities of success draw investors to locations earlier in the sequence, but, at the same time, these low probabilities reduce the prospects for funding (see Expression 4). As the probabilities get large (close to 1), the tendency is for investors to locate close to the end of the sequence when I_3 is large relative to I_1 and I_2. Finally, as the "location" of Stage 2 moves closer to Stage 3 (that is, the requisite expertise is more commercial than scientific), the chosen location ℓ^* moves closer to 1, indicating that the mix of scientific and commercial knowledge at intermediate stages affects the location decision.

The most significant insight from this model emerges when we allow Stage 1 investments to be funded by an outside, noneconomic actor. As we discuss above, the development of a Valley of Death depends upon the presence of noneconomic activity at Stage 1 of the innovation sequence. Let us take an admittedly extreme case in which this noneconomic activity removes entirely from the private investor the need to invest in Stage 1. In that extreme case, investors will choose the location,

$$\ell^* = \frac{xI_2 + P_2 I_3}{I_2 + P_2 I_3}, \tag{7}$$

which will always be between Stage 2 and Stage 3. With opportunities to invest in Stage 1 effectively precluded by the noneconomic activity, the private investor will respond by locating its R&D investment efforts further away from Stage 1

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53 Cross sectional variation in this relationship across projects or industries should allow for empirical testing of the role of lender location on basic research and innovation.

and closer to the end of the innovation sequence (ℓ^* gets closer to 1).[54] In cases where I_3 is relatively large, the investor will locate much closer to Stage 3 than 2. That action has the effect of increasing the risk premium at Stage 2.

This simple model shows that noneconomic activity that supports Stage 1 basic research to the exclusion of later stages may actually encourage investors to locate closer to the end of the innovation sequence. If this decision increases the risk premia at Stage 2, then we expect to see fewer projects funded at this intermediate stage. The result would be the widening of the Valley of Death, a phenomenon also created by the noneconomic activity.

That said, our analysis is not a critique of government funding of basic research and development. As discussed above, there are important and legitimate reasons for the public sector to support basic R&D efforts. But practically, one cannot ignore that this activity might have an impact upon private sector investment decisions. The government has for decades funded basic research with less focus on intermediate stage projects and our model predicts that investors today will have responded to that fact.

D. *Investor Specialization at Multiple Locations*

In the above analysis, we assumed that investors locate at a single location. Now, we consider the case where an investor can locate at many locations, but each location requires the investor to incur sunk cost E (e.g., due diligence costs and project specific expertise).[55] When making the location decision, the investor will choose more than one location if

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[54] This result is apparent, since I_1 is positive in Equation (6). We note that our model assumes a fixed quantity of potential investment opportunities at each stage of the innovation sequence with or without the intervention of a non-economic agent. In fact, one could argue that a large presence of a non-economic agent at Stage 1 could increase the investment opportunities at Stage 2 simply by increasing the quantity of potential Stage 2 projects. This change may move firms closer to the middle. Further, in Equation (7), we assume that the non-economic motivated support covers all basic research; this assumption is obviously an overstatement. Many projects funded by the noneconomic activity may not be substitutes for the projects of interest to private investors, thereby leaving the Stage 1 elements of Equation (6) intact, at least for some investors, in the location decision. In other words, the involvement of outsider at Stage 1 must substitute for private investment for there to be a location change.

[55] By sunk, we mean the costly information acquired during due diligence cannot be recovered or transferred to another project.

$$E < \frac{I_2}{2}(1-x)^2 , \quad (8)$$

where this condition *is an approximation when* I_3 is large relative to I_1 and I_2. If E is larger than $0.5I_2(1 - x)^2$, then it is cheaper to locate solely at ℓ^*.

While Expression (8) is not terribly intuitive, the key point is that small increases in sunk costs (like project-specific due diligence) make locating in multiple locations less likely, other things equal. Thus, investors may specialize at a single location if locating requires a sunk cost E that is sufficiently large relative to the investment, including due diligence costs that are unique to a particular (or particular type of) project. Also, reductions in the required investment (I_2) make the condition more difficult to satisfy (E constant), and intermediate stage projects often require smaller investments. The combination of high costs and small investments will incent investors to locate away from intermediate stages in the innovation sequence, which would contribute to the presence of a funding shortfall, and in the presence of noneconomic activity at Stage 1, exacerbate the Valley of Death.

The intuition of this analysis occurs frequently in the literature on venture capital investing. Lerner (1998) observes that "[v]enture capitalists may have eschewed small investments because they were simply not profitable, because of either the high costs associated with these transactions or the poor prospects of the thinly capitalized firms." Lerner also notes that "[b]ecause each firm in his portfolio must be closely scrutinized, the typical venture capitalist is typically responsible for no more than a dozen investments. Venture organizations are consequently unwilling to invest in very young firms that only require small capital infusions."[56] Richard Meyer echoes this common view, noting

> [Venture Capital] firms have matured, now usually raising and managing larger pools in the range of hundreds of millions of dollars. And with this change they no longer expend the time and funds needed to manage small investments; rather, they look to

56 Lerner (1998), *supra* n. 9.

> fund and manage a small number of multimillion dollar investments.[57]

Further, many commentators have observed that investor specialization at intermediate stages of the innovation sequence is very difficult. Intermediate stages often require both technical and commercial expertise as the project moves away from "pure knowledge" toward, but well short of, commercialization. This combination of knowledge assets may make the cost of locating at intermediate stages much higher than locating at either the early or late stages of the innovation sequence, where knowledge is more specialized. If, for example, the uncertainty giving rise to the substantial information premia at intermediate stages is merely the combination of moderate amount of two sorts of uncertainty, one "scientific" and the other "commercial," then specialization may not be readily feasible.[58] Rather, firms can spend resources to gain scientific expertise, or commercial development know-how, but the intermediate stages may involve not some third sort of uncertainty, but instead merely intermediate quantities of the other two kinds. In this view, this level and degree "specialization" is effectively impossible and can only be mimicked at a high cost.

The problem of coordinating knowledge in the innovation sequence was described clearly by Robert Frosch, who led the GM Research and Development Center from 1982 to 1994:

> There is a kind of Heisenberg uncertainty principle about the coordination connections that are necessary in R&D. One needs all of these deep connections among kinds of knowledge, and the ability to think about the future, that works best in an institution that puts all those people together. One also needs connection with the day-to-day, market thinking, and the future thinking of the operating side of the business, which suggests to many that the R&D people should be sitting on the operating side of the business. This is an insoluble problem; there is no organizational system that will capture perfectly both sets of coordination….

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57 R. Meyer, *The Start-Up Enterprise Valley of Death*, VIEWPOINT, Capital Formation Institute (2006).

58 S. Markham (2002), *supra* n. 12, at 31 ("Product champions . . . need to successfully carry out nine discrete though complex activities.").

> There is no perfect organization that will solve this problem—the struggle is inevitable.[59]

Attempts to master the two types of knowledge required for many Stage 2 projects, therefore, will be costly, perhaps prohibitively so, thereby increasing risk premia at Stage 2 as specialization does not (or cannot) occur. Moreover, those efforts to master either of these tasks may largely be sunk. As a result, firms that must incur substantial sunk costs to obtain expertise that would allow them to raise funds for investments may not, in equilibrium, find it optimal to incur two such costs to get expertise in both "science" and "commercialization." This would merely require a lack of scope economies, combined with information premia that are not too large.

So, while we do observe some investors locating at intermediate stages of the innovation sequence, high sunk costs coupled with low investment amounts may represent a significant deterrent to large numbers of investors locating there.[60] Perhaps this explains why investors that locate at intermediate stages on the innovation sequence are often characterized as exceptions rather than the rule, and why there is talk of a Funding Gap and a Valley of Death at intermediate stages.

E. *Empirical Implications*

The models presented here provide some guidance for empirical analysis on the Valley of Death. The factors that may create a Valley of Death will vary substantially by industry and project, thereby providing cross-sectional variation that can be exploited. For example, our conceptual framework may provide some guidance on why a Valley of Death is generally regarded as absent in some industries such as pharmaceuticals.[61]

First and foremost, in the context of our model, the presence of noneconomic activity is necessary for a Valley of Death to emerge. Since government involvement in basic research varies by project types and industries, the

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59 R. Frosch, *The Customer for R&D is Always Wrong!*, 39 RESEARCH TECHNOLOGY MANAGEMENT 22 (1996).

61 Frank *et al*. (1996), *supra* n. 30.

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relationship between noneconomic activity and the Valley of Death may be quantifiable.

Further, our analysis indicates that we would expect to see fewer funding problems at intermediate stages when the ratio of investment size to sunk costs is small. In industries where due diligence has a low degree of sunkeness, perhaps due to the fact that the expertise obtained for one project is transferable to another, investors will more readily locate at intermediate stages. Also, a Valley of Death is less likely to occur when the Stage 2 projects require mostly technical or mostly commercial expertise, since Stage 2 will be closer to those stages where funding is more readily available. The cross sectional variation in the degree of sunkenness of due diligence and the nature of Stage 2 expertise can be exploited by empirical models.

F. *Caveats*

Our approach is largely theoretical and is not intended to be a formal or complete model of research and development decisions, but it is consistent with other empirical and colloquial research in this area. Our analysis reveals several interesting observations on the causes of a Valley of Death and identifies several other areas of inquiry on the role of government in research and development. We recognize that our efforts here are limited and incomplete. We do not exhaust all possible theoretical avenues in search of a cause for a Valley of Death; our attention is limited to a few. The Valley of Death is a complex problem, and this is made increasingly apparent, at least to us, in our efforts to uncover its nature. This Project is certainly not the last word on this issue, and to a large extent we view it only as a starting point for a more detailed and theoretical analysis of the Valley of Death. Further research is obviously warranted, both on the Valley of Death itself and the optimal allocation of government funding of research across the innovation sequence.

VI. Summary and Policy Questions

The innovation process involves more than simply making new discoveries—for society to benefit, those discoveries must be translated into useful and innovative products, services or processes that are diffused and integrated into the economy as a whole. The Valley of Death—described as the place "where good lab discoveries go to die because they lack the funding necessary to become a commercial product"[62]—is often cited as a key roadblock to this translation process. Given the substantial support that government provides for R&D activity, it is important to understand why such a roadblock may exist and how it can be overcome.

In this PAPER, we provide policymakers an economic conceptualization and explanation of the Valley of Death. There has been substantial research on this topic but we focus our attention one aspect—namely, we aim to understand why the Valley of Death is a "valley." Any explanation for the Valley of Death must explain why the valley is surrounded by "peaks" on both sides. That is, one must understand why funding for basic research and late-stage commercialization R&D projects is more readily available while funding at the intermediate stage may be relatively scarce. Our research indicates that a Valley of Death can only emerge due to the presence of "noneconomic" investment activity into Stage 1 basic research, including the government and other entities. This noneconomic activity at Stage 1 can create the rift at Stage 2 commonly known as the Valley of Death.

We also observe that the Valley of Death may, in fact, be a natural and expected consequence of noneconomic activity at Stage 1 of the innovation sequence. This fact is not an indictment of such intervention, because that activity is likely to increase social welfare by increasing the overall level of innovation in the economy. Indeed, the United States spends more on basic research and development than any other country in the world, and there are obvious social and economic benefits from this investment. That intended result is likely more important than the unintended rift or valley that the intervention creates. Nevertheless, if the Valley of Death can be attenuated in an economically rational way, doing so will increase economic welfare and the productivity of government R&D investment.

This analysis opens up certain questions for technology policymakers, which include but are not limited to:

- Should government increase financial support for intermediate (applied) stage projects?

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62 Heller and Peterson, *supra* n. 28.

- Rather than increase the overall level of support, should the government's support of research be re-apportioned between basic and applied research? What is the optimal allocation of a fixed level of government support of research between the various stages of the innovation sequence? Would social welfare be increased if funds were diverted from basic research funding and used to fund the further development of the successful basic research projects?

- Should increased funding for intermediate stage projects be directed at existing programs such as the Advanced Technology Program or the Small Business Innovation Resource program? Or, are there other organizations or organizational structures better suited to the task? Would public-private partnerships be more effective at facilitating the flow of projects through the innovation sequence?

- Foreign governments also invest heavily in R&D, and studies show that the country in which research is converted into innovation captures most of the gains from such innovation.[63] If the U.S. fails to follow through on commercialization of the fruits of its basic research activities, are these taxpayer-funded basic research advances liable to be appropriated by other countries that may focus their R&D expenditures on Stage 2 activities? What will be the impact on jobs, economic development and global competitiveness if this were allowed to happen?

- Does the current tax code make any distinction between Stage 1 or Stage 2 investments by the private sector? Should it? Would favorable tax treatment facilitate the emergence of private funding sources at the intermediate stages? For example, should tax advantages be available only to private firms that invest in both basic Stage 1 research and Stage 2 development?

- Are there institutions and policies that can reduce information asymmetry and sunk costs for investors at intermediate stages of the innovation sequence? To what extent can patent policy for

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[63] *See, e.g.*, A. Benvignati, *The Relationship Between the Origin and Diffusion of Industrial Innovation*, 49 ECONOMICA 313 (1982).

government-funded basic research play a role in lowering the sunk cost for intermediate stage investments?

- The Byah-Dole Act of 1980 awards universities and other nonprofit organizations patents for research undertaken pursuant to a federal grant.[64] As a result, Technology Transfer Offices at universities play a large "gatekeeper" role. How effective is this process? Do Technology Transfer Offices use this position to reduce these information asymmetries and sunk costs? Do ineffective offices exacerbate those issues? Should the federal government oversee the activities of these offices to ensure that those entities are adequately lowering the entry costs for Stage 2 investments?

This discussion of policy alternatives is by no means complete, and we do not suggest any one particular approach. But our research does show that the Valley of Death is a phenomenon that may, in fact, be a consequence of the U.S. Government focusing its R&D investment activities almost exclusively upon early-stage, basic research, with only scant attention paid to intermediate stage projects. As a result, policymakers should strive to study and explore all methods of ensuring that the innovation process moves forward unimpeded, as society will only benefit from discoveries and inventions that are ultimately implemented in the production of goods and services.

64 35 U.S.C. § 200, *et seq.*