ARTICLE

INCONVENIENT TRUTHS: INTERPRETING THE ORIGINS OF THE INTERNET

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A conventional economic narrative provides intellectual underpinnings for governments to subsidize research and development ("R&D") that coordinates risky research to benefit many in society. This essay compares this narrative with the origins and invention of the internet. Are the historical facts consistent with the conventional economic narrative? Does the conventional economic narrative offer a complete explanation for why government subsidized R&D related to the internet produced high economic value? The essay shows why that narrative is consistent with historical experience, and incomplete in crucial respects. To remedy incompleteness, an analyst needs to appreciate the role of lead-users and good governance of technology transfer. Accounting for such factors, the essay develops a number of implications for technology policy.

INTRODUCTION[1]

The conventional economic narrative for federal subsidies of Research and Development (R&D) finds its intellectual roots in the economics literature about R&D. A large conversation covers all aspects of this topic, and blossoms in many directions.[2] A summary goes like this: federal support for R&D overcomes the predictable inadequacies with privately financed R&D. Private firms shun risky and scientific inquiry that results in diffused future benefits. Private organizations cannot capture sufficient value in such circumstances, and so, absent any extraordinary action from a government, private organizations face low incentives to invest in the R&D. That holds even when those (expected) benefits add up to far more than needed to justify the expense. Governments subsidize scientific research because government possesses the ability to coordinate and undertake risky actions that benefit many in society.

This narrative, which for convenience will go by the label "the conventional economic narrative," plays a central role in U.S. federal support

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[1] Some parts of this draws from previous writing, notably, SHANE GREENSTEIN, HOW THE INTERNET BECAME COMMERCIAL: INNOVATION, PRIVATIZATION, AND THE BIRTH OF A NEW NETWORK (2015), and Shane Greenstein, *Nurturing the Accumulation of Innovations: Lessons from the Internet, in* ACCELERATING INNOVATIONS IN ENERGY: INSIGHTS FROM MULTIPLE SECTORS 189 (Rebecca Henderson & Richard Newell eds. 2011).

[2] The historiography of the economic literature related to government sponsored R&D covers considerable ground that would take us far afield. Many date the literature to Kenneth Arrow, *Economic Welfare and the Allocation of Resource for Invention, in* THE RATE AND DIRECTION OF INVENTIVE ACTIVITY: ECONOMIC AND SOCIAL FACTORS 609-626 (Richard Nelson, ed., 1962) (at the time of this writing, Google Scholar indicates that Arrow's article has garnered more than one thousand citations. There has been considerable writing on the economics of R&D in this vein, and a thorough historiography would take several books.). *See generally* Kenneth Arrow, *The Economics of Inventive Activity over Fifty Years, in* THE RATE AND DIRECTION OF INVENTIVE ACTIVITY REVISITED (Josh Lerner & Scott Stern, eds., 2012) (reflecting on fifty years after the original); JONATHAN GRUBER & SIMON JOHNSON, JUMP-STARTING AMERICA, HOW BREAKTHROUGH SCIENCE CAN REVIVE ECONOMIC GROWTH AND THE AMERICAN DREAM (2019) (continuing this view into the context of the current U.S. R&D system).

for R&D, primarily at the National Science Foundation ("NSF") and the National Institute of Health ("NIH"), and elsewhere within the federal government. It underpins tens of billions of dollars of federal R&D money in health, biology, physics, engineering, computer science, and more. Moreover, it offers a view of the role of the boundary between the public and private R&D in the economy. Private firms perform R&D when the incentives exist, and government pays for R&D when the societal benefits exist, but the private incentives are insufficient. If governments properly execute the portfolio of R&D, and if researchers correctly anticipate (on average) where their efforts could have the largest payoffs to society, according to this conventional economic narrative, years later the R&D should result in productivity gains in many (typically knowledge-based) parts of the economy, where new knowledge has created opportunities for economic growth.

This essay has one goal: to compare the conventional economic narrative with the origins and invention of the internet. This comparison starts from a position of comfort, in that the conventional economic narrative seemingly sits comfortably next to common understanding of events. Two graduate assistants in Len Kleinrock's UCLA lab first logged into their Interface Message Processor ("IMP") in August of 1969.[3] Internet historians recognize that event as the first of thousands of messages using inventions and prototypes that led to today's internet, much of which have been subsidized by federal money for more than two decades.[4] It is also widely believed that the diffusion of these inventions into private commercial services caused an economic boom in the late 1990s. Given this common understanding, not surprisingly, the internet has become Exhibit A to illustrate how government support for R&D can yield valuable innovations that contribute to economic growth.

Unlike the politics behind internet policy,[5] the correspondence between

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[3] An IMP was the earliest prototype for what we today call routers. These are nodes in a network, designed to move packets of data. To communicate with each other, both IMPs must use the same protocols, or computer commands, to organize, send, and receive data. The IMP at UCLA was seeking to communicate with another at the Stanford Research Institute.

[4] *See, e.g.*, JANET ABBATE, INVENTING THE INTERNET (1999) (providing thorough analysis of events at DARPA and NSF*)*; ARTHUR NORBERG ET AL., TRANSFORMING COMPUTER TECHNOLOGY, INFORMATION PROCESSING FOR THE PENTAGON, 1962-1986 (1996) (providing thorough analysis and original interviews of events at DARPA); MITCHELL WALDROP, THE DREAM MACHINE: J.C.R. LICKLIDER AND THE REVOLUTION THAT MADE COMPUTING PERSONAL (2001) (tracing Licklider's influence).

[5] Several prominent U.S. politicians, most notably Al Gore, hitched agendas to the internet. There exist cartoonish versions of these claims, largely affiliated with numerous Al Gore jokes. *See* Richard Wiggins, *Al Gore and the Creation of the Internet,* FIRST MONDAY (Oct. 2, 2000), http://www.firstmonday.org/issues/issue5_10/wiggins/*). See also* GREENSTEIN (2015), *supra*

the conventional economic narrative and actual historical events has not received much scrutiny, presumably because they seem to sit comfortably together. What would an informed examination show? That comparison motivates this essay, which explores related questions: are the historical facts consistent with the conventional economic narrative? Why or why not? Does the conventional economic narrative offer a complete explanation for why government subsidized R&D related to the internet produced high economic value? Why or why not?

The first section of the essay analyzes a few examples that illuminate the broad historical outline behind the internet's development. The first conclusion arises easily: the facts appear consistent with the conventional economic case for subsidizing R&D on a broad level. Yet, the conventional narrative errs in two important respects that make such consistency unsatisfying. For one, the conventional narrative contains a retrospective bias that misinterprets the motivation for creating the internet, and, for two, it compresses a sequence of events into a singular invention. Those lead to omission of crucial features of the experience that led the internet to have such a large economic impact. In short, consistency is not near completeness. The conventional economic narrative, by itself, does not explain why the internet created large value. More is required.

The second section of the essay offers one remedy to incompleteness. It stresses events related to both the internet's inventiveness and to its deployment throughout the universities of the U.S. This part of the essay offers a framework with the label, "lead user," and summarizes a set of observations about the first users of the internet and their inventions. Lead user frameworks have a long history in economics and managerial scholarship for innovation. The approach directs attention at innovations initiated by early users, enhanced by learning from operational experience. This framework provides insights about why government stewardship led to some innovations the conventional narrative would otherwise overlook. It also underlays implications for R&D policy that partially overlap with, and contrast with, those derived from the conventional economic justification for subsidizing R&D.

The third section of the essay introduces one additional set of observations to remedy the incompleteness; stressing events related to moving the internet from government stewardship to private hands. This part of the essay offers the label, "good governance of technology transfer," because this section summarizes observations about lessons from the experience transferring internet technology into private hands. This section

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note 1, at 65-68 (explaining the historical origins and their (lack of) veracity).

stresses where governance had consequences for the creation of economic value from the internet, and it illustrates lessons about how to manage this transfer, and *how not to*. As with the other sections, these are lessons that the conventional narrative overlooks, and they are central to understanding how the internet created value.

Several implications follow from this assessment. For one, this essay offers a (narrow) warning to (my fellow) innovation economists to *not* rely exclusively on the conventional narrative to understand how the internet developed and why it had a large impact on the economy. While the internet can illustrate the conventional economic narrative, the narrative alone is not enough to explain the most salient features of events, in particular, why events around the privatization of the internet created so much value. The essay also offers (a more broad) warning for any future policy. Any lesson based solely on the conventional narrative is unlikely to be adequate for creating economic growth from government-subsidized innovation. Attention to concerns about lead users and good governance must accompany any subsidy to R&D to bring about innovation with large societal impact.

Finally, and perhaps more controversially, the essay contains other cautionary lessons for future federally subsidized R&D. The assessment implies it will be difficult to recreate high-impact technical inventions with government subsidies when events stray outside the conventional economic narrative, as any sufficiently ambitious attempt will tend to do. The value from decades of federal investment in R&D in such cases depends on whether some future decision makers show good judgment at the right moments. Said simply, successful R&D alone is insufficient to create value. Good policy must accompany it.

This essay aims at the concerns of economic technology policy, and owes considerable debt to the work of internet historians who have extensively documented its origins. However, this essay does not aim to uncover new historical insight. Rather, as stressed, it aims to help those familiar with the conventional economic narrative make sense of events about which they may be unfamiliar. Accordingly, it provides details in an accessible presentation to those unfamiliar with the internet's history. With those goals in mind, it would be counterproductive for the essay's goals to offer the history of invention for its own sake, and it also would be unsatisfying to wave away detail with a wistful "it's complicated." That leads to an essay that stresses "illustration instead of extensive analysis" and "a bottom line instead of pedantic detail." The essay generously deploys variations on the phrase "the curious reader can follow the footnotes."

I. THE CONVENTIONAL NARRATIVE

The experience with the internet appears consistent with the conventional economic narrative about government subsidy of R&D. To illustrate, it is necessary to provide a selective reading of the history of the internet that (conveniently but judiciously) does not dwell on every detail.

A. *Consistency and Illustration from History*

The history of budgets and governance align with the conventional narrative. Long before there was a major industry supplier, and long before any private supplier invested in developing packet switching, the U.S. military budget provided funds for the efforts (i.e., prior to 1985). NSF, with some extra help from special Congressional allocations,[6] largely served as the source of funds for invention from 1986 until some point near the end of government involvement, somewhere into 1993-95. Even then, NSF continued to fund frontier computer science.

The R&D subsidies from the government do also seem to fit a view of sagacious choices among the portfolio of projects by program managers who were forward-looking; aiming at long-term risky gains that private industry avoided tackling. Before any inventive academic or well-funded laboratory in a private firm had invested much in anything more than a few theoretical sketches and visionary statements, in the 1970s the U.S. military's R&D arm, the Defense Advanced Research Projects Agency ("DARPA"), hired program managers to initiate and develop packet switching,[7] accelerating its earliest incubation as a viable technology. A particular implementation of packet switching, initially worked out in the 1970s, became the foundations for the protocol designs and processes underlying what we today recognize as the internet.

What were DARPA's program officers searching for in the 1970s when it began funding what became the internet? An ideal technical solution that would move data between computer systems. A system that could enable the exchange of data and communication between computing systems without frequent human intervention would save the military time and personnel expenses, and help realize new strategic capabilities. Coordinating the

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[6] Later these allocations became the object of considerable political interest and misinterpretation. *See generally* Wiggins, *supra* note 5 (providing an overview of Al Gore's role in securing funding for NSF).

[7] Packet switching is a method of communicating data within networks. Data are grouped into "packets" with a header that directs the data to its destination. The remainder of the data is the "payload," which moves from origin to destination, where an application extracts the data. Packet switching technology underlies all internet communications today.

exchange, combination, and filtering of data between computer systems generated numerous logistical and organizational gains for military operations. Keeping communications functioning in spite of a blown/cut line, for example, has military value in hostile battlefield conditions.

One potential approach to these considerations, packet switching, held the promise to achieve these desirable attributes by allowing data to flow along multiple paths, unlike a circuit-switched telephone network in which calls follow a pre-set path programmed into central office telephone switches. Other potential attributes of packet switching also played a role. An inexpensive packet switching network could also cover large geographic distances, which could support the sharing of expensive computing resources over such distances. That too had self-evident military value. For example, military users in many locations–even potentially dangerous locations–could access databases housed in another (potentially safer) location.

Packet switching was but one of many DARPA projects on the frontiers of computer science.[8] While the demand for these innovative solutions was quite general, all the projects pushed the boundaries of computing at the time. Both "packet-switching" and "a network of networks" were budding theoretic concepts, lacking substantial prototypes. DARPA's administrators wanted innovative new designs for prototypes, and new processes for operating them. Those prototypes were the short run goal.

Another feature of the conventional economic narrative also appears in histories of the internet, namely, without government subsidy, no invention would have arisen. There was little or no private investment in internetworking. No other private entity would have undertaken the same efforts in internetworking–for example, to build a national backbone and supporting network–at least with an aim towards profiting from those efforts.[9]

A brief summary can illustrate. Close examination of the two largest and most capable firms in the U.S., AT&T and IBM, reveals they had no plans to deploy national networks in the 1980s. Summarizing book-length details, AT&T did not have such plans. That was so for numerous reasons related to the demands of its traditional business in telephony, the regulatory limits placed on its actions, and the outlook and perceptions that shaped managerial

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[8] The development of packet switching receives attention from all the historians of the internet. *See generally*, ABBATE, *supra* note 4; NORBERG ET AL., *supra* note 4; WALDROP, *supra* note 4; ALEX ROLAND AND PHILIP SHIMAN, STRATEGIC COMPUTING: DARPA AND THE QUEST FOR MACHINE INTELLIGENCE 1983 – 1993 (2002).

[9] DARPA did attempt to seed a private packet-switching industry in the early 1970s, but these efforts did not get far.

attention to priorities.[10] After AT&T's management realized the error of its perceptions in the 1990s, in late 1995-96 it began to promote a nation-wide consumer-oriented dial-up service for the internet, which realized some commercial success for a short time. In other words, these actions were salutary for the development of the internet as a commercial service, but also quite late.

Another highly capable and wealthy firm, IBM, explored the area in one research division in the middle of the 1980s, and pursued it after winning a bid for government contract (discussed more in section IIIB). Later, this same division at IBM, with help from IBM's legal team, would make one daring attempt to dominate U.S. networking, and it would fail (also discussed further in Section IIIB). It too developed a national dial-up service in the early 1990s, but only for its business clients. IBM's other divisions, who sold to all of IBM's private customers, largely ignored what the researchers were doing, and management in most parts of IBM continued to push proprietary versions of local networking equipment until the firm experienced its existential crisis in 1993-94. After restructuring its strategy between 1994 and 1996, IBM began promoting services using non-proprietary networking technologies, such as the World Wide Web.[11] In other words, the entire corporation switched approaches, which was salutary for the internet's development as a commercial service, but, like AT&T, it also came quite late.

Summarizing, even with some optimism, contemporaries in the 1970s and 1980s, and even into the early 1990s, could not have, and did not, believe that any firm would provide non-proprietary internetworking services in the U.S. for a long time, at best.[12]

Finally, as a further boost to this conventional narrative, the invention and deployment of the internet also seems to have resulted in technological advance that underpinned impressive and widespread economic growth. The privatization of the internet is associated with the boom in economic growth in the late 1990s, and the timing appears to be more than coincidence. The privatization of the internet backbone finished in June of 1995. Netscape's

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[10] This is an extensive story. *See generally* GREENSTEIN (2015), *supra* note 1, at Chapter 2 and 3; ABBATE, *supra* note 4; NORBERG ET AL., *supra* note 4 (explaining the early development of packet switching and explanations for AT&T's lack of interest). *See also* Greenstein (2015), *supra* note 1, at 224-227 (describing its dial-up service).

[11] *See* GREENSTEIN (2015), *supra* note 1, at 77-82 (detailing IBM's early involvement in NSF internet); 272-282 (providing an analysis of its change in strategy).

[12] Other forward-looking efforts at internetworking, such as Minitel in France, were outside the U.S., and largely ignored within the U.S. Efforts to build national electronic mail services in the U.S. – from IBM, Lotus Notes, Compuserve, and others, also largely emerged in the 1990s, building on earlier efforts within BBS systems, and the internet eventually displaced them. *See* GREENSTEIN (2015), *supra* note 1, at 138-148 (adding further details).

IPO took place in August of 1995, as did the rollout of Windows 95 with Internet Explorer 1.0. By December of 1995, Microsoft announced its change in direction, and its intention to invest heavily in the internet, publicly signaling the beginning of what later observers labeled "the browser wars." Only a few months later, more than a thousand dial-up internet service providers ("ISPs") would offer service throughout the U.S., and that continued to grow for years. These events catalyzed adoption of the internet in millions of households and business establishments over the next decade.

Economic growth exploded for several years thereafter. An investment boom ensued in the carrier industry, as did an investment boom in private establishment use, as did sophisticated business uses for the internet. IT consulting industries grew rapidly in size to help. This widespread activity served as the engine behind more than three percent growth per annum between 1995 and 2002, and sometimes four percent. That uninterrupted growth was the highest sustained economic growth rates experienced in the U.S. since the 1960s, and, as of this writing, that rate of growth has not arisen in two successive years the two subsequent decades. In other words, it appears that the privatization of the internet, and its subsequent growth, caused a boom in economic growth and prosperity, with foundations in technologically-enabled new investments.

Summarizing, the experience with the internet appears consistent with the conventional economic narrative. Moreover, it also appears consistent with the view that government-subsidized technical innovation can yield substantial economic growth.

What is inadequate about the preceding comparison of the conventional narrative and the historical facts? While an outline of facts is consistent with the narrative, the conventional narrative contains a retrospect bias that oversimplifies the innovation process. In addition, it compresses events into a simple narrative. Both result in overlooking the role of motivation and governance.

B. *Motivation for Invention*

When applied to the history of the internet, the conventional narrative contains a retrospective bias. It presumes the later outcomes were intended consequences, and grafts motives onto DARPA's managers that were not present at the time of the decisions. Specifically, the conventional economic narrative presumes that because an economic boom followed invention, the anticipated economic benefits from invention motivated DARPA's funding. That is, at best, a misleading way to characterize the motivation that led to funding the inventive activity.

While decision making at DARPA was forward-looking, it was also parochial in its orientation. DARPA had a mission, to serve the military. That outweighs every other consideration. Broadly, and for a variety of reasons related to its origins, DARPA's mission was to develop radical new concepts and operations to transform military operations through development of new technologies.[13] The potential value to the military was sufficient motivation for such funding, and in the case of internetworking technology, there were plenty of military use-cases to justify developments.[14]

Laws such as the Mansfield Amendment of 1973 also proscribed the mission.[15] Bluntly stated, the Mansfield Amendment of 1973 expressly limited appropriations for defense research (through ARPA/DARPA) to projects with direct military application. To be sure, this is an elastic boundary, and allows for quite a broad range of subsidized activities. It does not preclude funding R&D that leads to benefits for non-military purposes. Whether those non-military uses arise or not, however, was largely irrelevant to the decision to fund R&D for the military. In short, while funders of federal R&D vaguely justified some inventions with visions of what large scale deployment would practically entail, scant evidence suggests DARPA's decision makers used economic reasoning.

Economic policy analysis presumes decisions use a forward-looking cost/benefit analysis. That does not preclude making a cost/benefit calculation of the costs and gains from invention of the internet, but that calculation's historical validity only applies to calculations done with the benefit of hindsight, and should be explicitly acknowledged as retrospective.[16] It would be historically inaccurate as an *ex ante* characterization of forward-

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[13] The initial impetus for Congress to establish DARPA came from the Sputnik crisis, and originated out of concerns that the U.S. military lacked proper institutions to retain an innovative edge. *See generally* NORBERG ET AL., *supra* note 4; WALDROP, *supra* note 4.

[14] *See* NORBERG ET AL., *supra* note 4; WALDROP, *supra* note 4 (discussing criteria for assessing research are discussed in both. For example, Licklider's three criteria for funding research still sound prescient today: "1. The research must be excellent research as evaluated from a scientific or technical point of view; 2. The research must offer a good prospect of solving problems that are of interest to the Department of Defense; 3. The various sponsored efforts must fit together into one or more coherent programs that will provide a mechanism, not only for execution of the research, but also for bringing to bear upon the operations in the Defense Department the applicable results of the research *and* knowledge and methods that have been developed in the fields in which the research is carried out.").

[15] *See* NORBERG ET AL., *supra* note 4 (stressing that DARPA's funding of packet switching research in the 1960s and 1970s met concerns about whether the funding was relevant to military mission, as required by the Mansfield Amendment of 1973. The research anticipated enhancing the "command and control" capabilities of commanders increasingly reliant on their computing resources).

[16] *See* GREENSTEIN (2015), *supra* note 1, at 125-29 (making this argument during the discussion of the cost/benefit of the government subsidies that resulted in the invention of the commercial Internet).

looking motivation for subsidizing R&D at DARPA.[17]

Why care about this retrospective bias? Because it is more accurate to say DARPA's actions were "mission-driven." R&D that arises from fulfilling a specific mission can have *unintended economic consequences* when the technology becomes deployed in an unanticipated or unexamined application with little relationship to the mission. It is also more appropriate to ask why outcomes succeeded *in spite of the lack of foresight.* As discussed Section III, these unintended consequences make the policies for governance of technology transfer particularly important for understanding the creation of value in private markets. In addition, it suggests a lesson: In designing policies intended to replicate successful subsidy programs of the past, one should always take into account the complex motivations that shaped those subsidy programs, and the likelihood that different complex motivations will shape the results from subsidies in the future, leading the future to diverge from past experience. It also implies that *without attention to unanticipated applications,* mission-driven R&D will not tend to lead to new applications with economic consequences outside of military uses. Such observations are missing from the conventional economic narrative. This lesson also refocuses the general question about technologies that have unanticipated economic benefits: What made the technology and institutions so resilient and adaptable in the presence of unplanned circumstances?

C. *Not a Single Invention*

The second retrospective error arises from compressing a long series of inventive actions into one. While convenient for narrative expediency, compression misleads when discussing policy lessons from the internet. Particularly in common retelling, compression tends to focus attention on DARPA's initial funding, while overlooking the importance of later actions. It also overlooks some of the characteristics of the internet that made it so adaptable, which, as the prior paragraph just noted, is central to understanding the impact of this technology (and others developed by government agencies with a mission-orientation).

Begin with a simple fact, and one made by many historians of the internet. Unlike many other breakthrough technologies, the internet did not originate as one epiphany in the head of one lone innovator genius, who doggedly developed an invention after a period of sustained prototyping, leading in a linear direction from idea to invention to refined prototype to commercial

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[17] *See* Shane Greenstein & Frank Nagle, *Digital Dark Matter and the Economic Contribution of Apache,* 43 RESEARCH POL'Y 623 (2014) (attempting to calculate such a cost/benefit and unsurprisingly finding the gains far exceeded the costs of invention).

product. Like many other major technical breakthroughs, the internet is not, and never has been, one single idea, or one technology with a fixed set of characteristics and features. It has undergone considerable evolution from its initial development as later innovators added new improvements, experience yielded new insight that redirected priorities, and new use-cases merited further refinements. In this case, the improvements came from many contributors over many years.

As the evolution is extremely well-documented by many technical historians, there is no need to belabor the observation. A little detail, however, can go a long way for this essay's purposes. It is useful to divide the internet's development into four periods.

1. *Initial prototyping.* The first set of frontier inventions took place during the period in the 1970s and early 1980s, when DARPA was the sole funder of inventive acts and operations, and the basic prototypes for packet-switching were first engineered. So too was the specific implementation at DARPA that grew beyond a small set of prototypes, albeit the result was not technically straightforward at the time. As a simplified label for what resulted, many call this suite of invention and operations by the name "TCP/IP," the specific design for protocols, though contemporaries built much more around TCP/IP to make it viable. The internet still uses a descendent of TCP/IP today. Books can be, and have been, written about these inventions, and the events that spawned them.

2. *Refinement of the network by the National Science Foundation (NSF).* In the middle of the 1980s, parts of the TCP/IP-based Internet were transferred to NSF, which chose to continue to use TCP/IP protocols and related processes.[18] Under NSF governance, the Internet acquired a range of new refinements to the protocols, and new institutions for supporting and routinizing them – much of which NSF and research university administrations paid for.[19] With both NSF and Department of Defense ("DOD") funding, further innovation took place in the domain name-server system ("DNS"), and BGP, the protocol that implemented "best-effort routing," which enabled multiple servers and pathways for data. This was also the period where the Internet Engineering Task Force became established, which still operates today. Its mission, institutionalizing the

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[18] *See* ABBATE, *supra* note 4 (explaining how DARPA transferred part of the internet to NSF because, in part, many civilian participants were frustrated by the challenges getting military clearances, etc., and NSF's leadership foresaw benefits to the U.S. academic research community).

[19] *See* ABBATE, *supra* note 4 (providing a detailed explanation. Until the NSFNET came into existence, there was only one network and one backbone, and BBN operated it. The scale was limited, and, in contrast, NSF anticipated supporting a much large network. Eventually the NSFNET therefore introduced additional backbones and regional carriers.).

evolution of protocol development for TCP/IP, came with the blessing of both the DOD and NSF, as well as their funding. At the time of these actions, nobody was forecasting with any particular confidence about whether the network would scale much beyond its core community of researchers. And that lack of confidence manifest as "chaos" about the direction of change, about which there was no agreement.[20] Altogether, these actions helped turn the Internet into a living decentralized and geographically-dispersed organization, capable of supporting hundreds of thousands of users, and, eventually, millions of students.

3. *Initiation of privatization.* During the early 1990s (and drawing on developments from the late 1980s), a third round of innovation ensued, and much of it was driven by the needs of privatization. Even at this late moment, nobody was forecasting the wide breadth of impact that privatization would have on the economy, nor was anybody planning for it. Rather, the focus was pragmatic, and oriented towards issues with daily operational processes. A private market could give rise to multiple backbone providers. The most important invention for this circumstance built upon BGP, and was an institutional one, which established routines for routing tables held at multiple locations, updated from a single source.[21] A large debate (further described in Section IIIB) surrounded the practices for data-exchange in a privatized system, where, to achieve national interoperability of communications, competing firms had to cooperate, and, at first, some were reluctant to do so. Initially several industry providers adopted practices that enabled multiple parties to act as non-monopoly carriers of data for the Internet, eventually hurt by, and then helped by NSF's policies for privatizing the internet.[22] This was also the beginnings of the pricing of data carrier services. Those institutions would continue to undergo evolution after the Internet privatized and began to explode as a commercial network, so it is inaccurate to say the government funding *solely* invented these processes.

4. *National deployment.* Fourth, and not trivially, in the early 1990s, Tim Berners-Lee invented the World Wide Web, and then began to deploy it as

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[20] *See* Janet Abbate, *Privatizing the Internet: Competing Visions and Chaotic Events, 1987-1995*, 32 IEEE ANNALS HIST. COMPUTING 10 (2010) (providing a characterization of the many points of view behind this chaotic period).

[21] *See* DAVID CLARK, DESIGNING AN INTERNET (2018) (explaining that NSF switched from the routing protocol Exterior Gateway Protocol ("EGP") and replaced it with Border Gate Protocol ("BGP"). The EGP protocol presumed a known pathway for connecting systems. BGP enables fully decentralized routing. To internet veteran David Clark, making this change was one of the earliest technical signs of the pending arrival of commercial network and the retirement of NSFNET.).

[22] The privatization of the internet backbone, which permitted private and public users to both use internet protocols and share assets for doing so, would have been very difficult to grow without these inventions.

a use of the internet as a non-for-profit open system. That expanded the functionality of the internet in ways that made it far more appealing to non-research users. It began to become widely adopted in the early 1990s, and it would spread even further as the internet privatized. Importantly, other university participants began to modify the Web with the invention of better webservers and browsers. At the University of Illinois National Center for Supercomputing Applications ("NCSA") a team developed the Mosaic Browser, which became the source for both Netscape and Internet Explorer (described in Section IIID). The University of Illinois also was the source of the web server that became the antecedent to Apache, the most popular web server for the next two decades (again, described in Section IIID). To summarize a long process, university researchers created much of these inventions, most received U.S. funding from NSF for their R&D, and, afterwards, private investors picked up the innovative activity, taking the innovations to market, where it sold to users.

What broad point emerges from recognizing this general sequence? Most important, observers make an error by being too breezy in common conversation by stating, "DARPA funded the invention of the Internet." NSF deserves much credit, and justifiably deserves top billing with DARPA. Seen from today's perspective, the invention of the Internet was not a single act, and had no single supporting organization behind the funding that led to the development of what firms and buyers use today. Its two-decade long development under government auspices was complicated and nuanced, involving multiple funders, mixing operation-oriented and research-oriented missions. Its primary use cases also changed over time, as did the composition of users. The orientation of innovations and refinements changed too, as did the identities of the primary innovators.

Why does that matter for deriving lessons aimed at technology policy from the conventional economic narrative? For one, a project of this scale, scope, and length did not happen on its own. It required managerial attention over multiple decades and different levels of technical complexity and policy complication. Indeed, as described in Section IIA, a crucial feature of DARPA's success resided in stating a clear mission for its efforts, even as the identity and goals of its stewards changed. The same is so for NSF, who played a crucial role after DARPA. The conventional economic narrative does not direct any attention at this accumulation of features, nor how government managers nurtured that accumulation.[23]

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[23] *See* Greenstein (2011), *supra* note 1 (explaining a number of institutional features and practices encouraged accumulation. Many of these practices later became the foundations for norms and practices of open source.).

Said another way, underinvestment in governance could have diminished the impact of the internet, and (as described in detail in Section III) was essential for its prosperity. It is also rather obvious that the program managers showed extraordinary competence and judgment. Managers had to work with (sometimes) minimal oversight from their agency heads, and (sometimes) direct intervention from Congress.[24] The conventional economic narrative overlooks these aspects, and does not provide guidance for future R&D policy about how to invest in such capabilities (and which sections III and IV stress).

II. LEAD USERS

The two retrospective biases take attention away from another pattern, well-known to historians of government use of frontier technology. Namely, the U.S. military and NASA served as a "lead user" in the many IT technologies in the 1960s and 70s.[25] "Lead-user" frameworks are a natural candidate for explaining aspects of the experience with the internet. It is important to appreciate because, as demonstrated several times in this section, it also yields policy lessons that differ from the conventional economic justification for subsidizing R&D.

A. *Lead Users at DARPA*

The "elevator pitch" for lead-user frameworks goes like this: a lead user faces needs before these needs have reached any other potential user. As a result, the lead user is highly motivated to address those needs with pioneering research and with inventive technologies, even prior to their development by market suppliers. Even if providers offer prototypes, in such settings the supplies from providers rarely, if ever, provide full functionality without modification, so users find that they must invent some of the technologies required for achieving the desired functionality.[26]

If the lead user succeeds in inventing the basis for a general-purpose

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[24] *See* NORBERG ET AL., *supra* note 4; Abbate, *supra* note 20 (discussing the inescapable tension between oversight and discretion at DARPA, and explaining the logic for why DARPA opted for giving program officers considerable discretion).

[25] *See* KENNETH FLAMM, TARGETING THE COMPUTER: GOVERNMENT SUPPORT AND INTERNATIONAL COMPETITION (1988); *see also* KENNETH FLAMM, CREATING THE COMPUTER: GOVERNMENT, INDUSTRY AND HIGH TECHNOLOGY (1989) (both exploring these themes with extensive analysis of many case studies).

[26] *See* ERIC VON HIPPEL, THE SOURCES OF INNOVATION (1988) (identifying with the framework offered by this sentence. This and related ideas have long been found in studies of early diffusion and adoption).

technology, particularly at an early moment in its development, lead users typically engage in "co-invention" with suppliers of general-purpose technologies. That activity aims at adapting the supplied goods to the user's perceived needs. Such activity seeks to take a general-purpose technology, and invent complementary prototypes and processes to yield value in specific circumstances and for a variety of specific use-cases. Additionally, lead user activity typically faces an array of challenges affiliated with the discontinuities implementing co-invention, especially when it alters existing organizational practice, and requires unusual efforts to jump-start wide-scale use by other users within the organizations.[27]

The lead user framework illuminates numerous crucial details of events. To begin, by the early 1970s, the U.S. military was already one of the largest buyers and users of computer equipment and systems in the world. In this era, each computing system was typically an island unto itself. None of these could communicate with another computer, nor pass files electronically between them in any automated way. As already noted, it is rather easy to make the case that the U.S. military faced issues with its own computing facilities and operations that no other user had yet encountered on the same scale, and those issues, by themselves, provided sufficient motivation to fund R&D to alleviate the issues.

An important feature of the lead-user framework in the private sector also yields important insights here, namely, the skunk works operates outside of normal operations. A skunk works is what large organizations in the private sector often formed when they pursue activities affiliated with being a lead user. A *skunk works* is an organizational home for frontier development projects.[28] Housed away from the main operations of an organization, sometimes in secret or with organizational barriers, and often with top

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[27] For an empirical example of co-invention at early adopters, *see generally* Timothy Bresnahan & Shane Greenstein, *Technical Progress and Co-Invention in Computing and in the Use of Computers*, BROOKINGS PAPERS ON ECON. ACTIVITY: MICROECONOMICS 1-78 (1996). This builds on the framework first introduced in Timothy Bresnahan & Manuel Trajtenberg, *General Purpose Technology: Engines of Growth*, 65 J. OF ECONOMETRICS 83, 83-108 (1995). A general presentation of the framework of co-invention can be found in Timothy Bresnahan & Shane Greenstein, *The Economic Contribution of Information Technology: Towards Comparative and User Studies*, 11 J. OF EVOLUTIONARY ECON. 95, 95-118 (2001).

[28] *See* BEN R. RICH & LEO JANUS, SKUNK WORKS; A PERSONAL MEMOIR OF MY YEARS AT LOCKHEED (1994) (explaining that the phrase, skunk works, originated from a project for the Air Force at a division of Lockheed Martin, where it described projects to engineer new airplanes. A special team pursued these projects, physically located away from regular operations. The division had called itself the "Skonk Works" after a phrase from Al Capp's *Lil' Abner* cartoon – the skonk works was a "secret laboratory" that operated in the backwoods. The label became well known throughout the industry, in part because it was considered humorous and saucy. *Lil' Abner's* publisher eventually asked Lockheed Martin to change it, and "skunk works" emerged from there.).

management support for these barriers, a skunk works typically tackles development projects of value to the future of the organization. With rare exception, such projects do not directly connect to short term operational or service missions.

Is it possible to view DARPA itself as the military's skunk works? Yes, to some extent, and to some extent no. The similarities are apparent in the discretion given to program officers, who held discretion to depart from routine operations, and did not measure their gains against short term operational goals. They could pick research stars to fund, hold them to informal understandings, and permit the researchers to pursue open-ended goals in their prototyping. The program officers often asked for broad proposals, picked lead researchers, made general agreements with them about the long term goals, funded their labs with uncommonly large amounts of money, and gave them large amounts of discretion to pursue those goals in the manner they saw fit.[29] In exchange for this funding, the researchers were required to attempt ambitious projects, participate in specific conferences, document and share their results with each other, and contribute to the training of a new generation of researchers, among other things.

DARPA's program for fostering innovations in computing departed from a key aspect of the skunk works practiced among military contractors, however, in the way it used new locations.[30] While some private firms located their skunk works in locations distant from operations to shield it from short term thinking, DARPA did more than just separate the location of the skunk works from the location of operations. It *administered* from D.C. to researchers geographically dispersed at many locations in research organizations and universities across the country, and did so out of necessity. DARPA sent money for projects organized by key researchers, who maintained their laboratories. Money also went to contracting research organizations.[31] Dispersed geography mattered in several ways. Innovative improvements arose and accumulated in different places, accommodating a diversity of viewpoints, and yielding a variety of lessons. Collectively the program began accumulating improvements from a diversity of sources.

That geographic dispersion also exaggerated another key challenge for any skunk works, monitoring progress. Precisely because a skunk works seeks to break with established processes to facilitate experimentation and protect

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[29] *See* NORBERG ET AL., *supra* note 4, at 1 (describing how program offices used their discretion).

[30] *See* NORBERG ET AL., *supra* note 4, at 17-19 (discussing the challenges of sourcing projects from geographically dispersed group of researchers).

[31] Such as BBN (in Cambridge, MA), the Rand Corporation (in Santa Monica, CA), and Stanford Research Institute (in Menlo Park, CA).

it from the objections of other organizations or their parent entity, a skunk works faces numerous challenges benchmarking progress of its researchers against existing procedures (which may provide benchmarks of increasing irrelevance). Its challenges are even greater when the participants in the skunk works create inventions for needs that most potential users have not yet even recognized, and reflect a diversity of opinions about the best future use-cases. Then no established practice serves as a benchmark.

Within DARPA, program officers directly performed the monitoring. Many program officers were technically sophisticated enough to follow specific advanced developments. In fact, DOD program officers often did the evaluation themselves or with a small set of consultations, and not necessarily using informal evaluation by peers. Some even contributed inventions to the efforts.

Despite the geographic dispersion, participants shared a sense of identity about the whole project, and the researchers were encouraged to share innovations with one another. Indeed, a set of processes emerged for commenting on one another's projects, and became the basis for the open processes (still in use today). Loosely coupled to one another through their common funding source, they shared scientific and engineering goals. Program officers encouraged this sharing.[32]

Comparisons with skunk works yield one additional insight about learning from experience. As the projects within a skunk works mature, it typically mixes engineering prototyping with expected operational challenges. This too occurred in the early years. The first and second generation of Internet researchers[33] got ideas from their own experiences and their own needs. Because inventers were also users, they were motivated to develop working prototypes into operational pieces that they and others could employ. Their experience introduced them to issues associated with refining and maintaining workable versions of their inventions in a functioning and operational network — and not just any network, but a network they developed and used.

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[32] *See, e.g.*, NORBERG ET AL., *supra* note 4, at 18-19; ROLAND & SHIMAN, *supra* note 8, at 2-4 (both building coherent scientific communities around nascent technologies was an explicit part of the mission of every program officer in this era).

[33] *See* Steven D. Crocker, *The Origins of RFCs*, *in* RFC 1000 - REQUEST FOR COMMENTS REFERENCE GUIDE (J. Reynolds & J. Postel eds., 1987), https://tools.ietf.org/html/rfc1000, accessed March 2, 2020 (explaining early internet research and RFCs). *See also* Barry Leiner et al., *A Brief History of the Internet, Version 3.32,* THE INTERNET SOC'Y, (Dec. 10, 2003), http://www.isoc.org/internet/history/brief.shtml (showing that there is no clean line between generations, but this is convenient language to use. "The first generation" of internet researchers grappled with engineering, creating the first packet switching applications and prototypes, and demonstrating the viability of the concepts. The second generation contributed to the existing infrastructure, and, along with the first generation, built applications and scale.).

The integration of innovations into immediate operation shaped the consensus about innovations and helped determine whether suggestions for new protocols merited attention. As improvements arose, routine processes embedded those improvements. If installation administrators did not think the innovations useful, they did not implement the proposals, nor use them. If they used the suggestion, the inventions were refined and began to accumulate additional improvements.

In the short run, mixing inventive activities with operational activities also oriented innovation. Although using a common network, each group of researchers began working in its own direction, with its own working prototypes, for its own use as well as use by others. Due to their common affiliation with DARPA and common use of the network (which became known as the DARPANET), the researchers began to make their prototypes interoperate with each other.

One illustration can help develop the insight in the importance of interacting with operations. Early Internet innovators quickly developed several applications with high value - file transfer, predecessors to what we today recognize as instant messaging, and electronic communication that became electronic mail.[34] Arguably, electronic mail was not the central innovation of the skunk works. Yet, every participant employed it, and its pragmatic value was recognized by participants. Many people made important contributions to the e-mail design in the 1970s and 1980s, and by the end of the decade all participants in the Internet made use of it. Another lesson from the experience with e-mail application innovation is that its usefulness was apparent at the time to the many participants in the DARPANET, but not to the sponsoring federal agency. As stated by Bob Kahn, DARPA "would never have funded a computer network in order to facilitate e-mail" because other goals were more paramount, and person-to-person communication over telephones appeared sufficient.[35]

The spread of e-mail highlights the essential paradox of a skunk works: protecting participants from operational concerns helps them point towards long term needs. Protecting participants from short term assessment and formal review also permits them to co-invent in unanticipated directions.

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[34] *See* Craig Partridge, *The Technical Development of Internet Email*, 3.2 ANNALS OF THE HIST. OF THE COMPUTING 3, 3-29, (2008); *Descriptions*, LIVING INTERNET HIST. (July 2009), http://www.livinginternet.com/e/e.htm (both providing extensive documentation of how subsequent technical improvements built on one another, beginning with an early project at the RAND Corporation in Los Angeles).

[35] *See* Stephen Segaller, NERDS: A BRIEF HIST. OF THE INTERNET 105 (1998) (explaining that the challenges of building a sound and pragmatic internetwork received the focus of most of the researchers, and the applications were not regarded as a high priority, even though these applications were useful and raised the value of internetworking).

However, at an early stage virtually nobody in an organization except the most technically sophisticated manager is able to monitor and assess whether the invention has succeeded in moving in a useful direction. In this case, it took talented program officers to manage a skunk works.

To summarize, the lead-user framework provides a useful set of observations for interpreting events during the earliest days of the Internet within DARPA. It provides insight into how the DARPA's mission translated into invention, and how its organizing principles replicated architectures found in other innovation organizations. It also reinforces the observations made in Section II that participants invented for their own parochial reasons, and with little foresight about the extent of its future impact on economic outcomes outside of the military.

B. *NSF as a Lead User*

The lead-user framework predicts that changes in identity of the organization funding the operations could change the direction of invention activity. If the operational purpose changes, so too could the learning that arises from operations, and the direction of innovation motivated by that learning. Once again, this insight about the direction of innovation would *not* arise from a conventional economic narrative for understanding subsidized R&D.

It is crucial to distinguish between NSF's funding for basic science in computer science, and its operations to support science. Funding for research did continue in the 1980s, and that activity falls within the standard economic narrative, and NSF *did* subsidize a variety of research and researchers in internetworking. It is, however, insufficient for understanding why NSF's stewardship of the NSFNET's operations brought about such a large improvement in the technology's ability to scale, which became crucial to its privatization and its high economic value.

The handover of DARPA's network to NSF potentially enhanced NSF's mission to support research.[36] NSF would take on managerial responsibilities for many aspects of the operations. While it handed operational responsibility for the backbone to the (winning) bidder, IBM/MCI and its Michigan based academic partners, responsibility for many other parts of the network resided with the universities, who supported interconnection with the growing network, and use by local students, faculty and researchers.

More to the point, the insight helps explain why the internet changed

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[36] *See* ABBATE, *supra* note 4 and Abbate, *supra* note 20 (both discussing how these were complex events and involved many unexpected consequences and challenges.).

when it transferred to NSF stewardship. In 1985, DARPA handed over control of part of the network to NSF for a number of reasons. It opened the network to the many civilian researchers interested in using it. By then, the community of innovators had evolved into a loose confederation of researchers from many locations, so this administrative change partly ratified what had already begun to happen informally. A new source of funding also introduced a new budgetary process, a new outlook about the future, and new set of priorities for a different set of operational needs.

Three overlapping needs at NSF became most salient at the outset. As with DARPA's motivation, much of NSF's investment was aimed at the creation of an electronic communication network among researchers. One application for communications also became focal: Administrators envisioned that packet switching would enable the movement of files between supercomputer centers and many universities. Second, NSF had aspirations for resource sharing. Supercomputers were expensive fixed investments with no geographic mobility. NSF initially aimed to use the internet to permit many researchers to connect with those supercomputers, enhancing use of the capacity without physical presence, and making greater use of the capacity and sharing the huge computing power they embodied.

A third aspiration for NSF concerned scaling for widespread use, and this aspiration would eventually have large consequences. It would require NSF to sample from a diversity of circumstances across the entire range of universities and colleges in the U.S., and accommodate these circumstances and test across them. NSF aimed to build a routine and reliable network infrastructure, making it easy to spread to every place of higher learning in the U.S. – universities, community colleges, and research institutes.[37] NSF eventually adopted a program to encourage connections to every university and college in the U.S., spreading connectivity far outside the small set of elite research-oriented universities on the frontier of internetworking.

NSF accomplished these three goals with the help of additional Congressional outlays. After the initial setup for supercomputers, the priorities for the third mission changed subtly, aiming towards investment aspiring to give a wide range of participants–students, faculty, and administrators–a taste for what the Internet could do to help them in their work, namely, transmit electronic communication, data files, news, and other

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[37] *See, e.g.*, Karen Frazier, *Building the NSFNet: A Partnership in High Speed Networking: Final Report 1987-1995*, MERIT NETWORK, INC. (1995), https://www.merit.edu/wp-content/uploads/2019/06/NSFNET_final-1.pdf (providing an extensive description of NSF's aims and accomplishments).

messages over long distances.[38]

The expanding goal required a system that would handle traffic of many orders of magnitudes greater than anything done to that point. It also required investment in routine administrative processes to support widespread use, which motivated development of easy-to-use software for facilitating student use. That led to many co-inventions to make electronic mail, file transfer, and (eventually) browsing accessible to non-technical users. Many universities trained their students in the internet, developed processes for enabling remote access (e.g., by dial-up modem), and permitted discretion to develop applications (such as email) that motivated adoption later.[39]

To summarize, the lead-user frameworks yield insights into many salient actions during the deployment of the internet, and these differ from the insights generated by the conventional economic narrative. Most important, the lead-user frameworks provide insight into the direction of innovation. Moreover, these actions improved the ability of the internet to scale for use by non-technical users, which turned out to be crucial for why the internet yielded such a large economic impact when it privatized. In short, lead-user frameworks fill in crucial gaps in this historical narrative, and, therefore, are likely to do so in any future effort.

III. GOVERNANCE DURING TECHNOLOGY TRANSFER

How did DARPA, and then NSF, generate a rich portfolio of unexpected discoveries around the internet instead of an accumulation of pointless incremental contributions? As already noted in Section II, governance of innovative activity played a key role. This next section focuses on a different set of governance issues, during the transfer of technology to private users.

A. *Channels for Technology Transfer*

Governance at NSF begins from its charter, which both specifies its mission and the limits to that mission. By the 1980s, NSF had a long history of living with a policy of "Acceptable Use" for any asset it subsidized with a grant, where "acceptable" meant it served a purpose in higher education.

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[38] *See generally* Abbate, *supra* note 20, and GREENSTEIN (2015), *supra* note 1, at Chapter 3 (explaining how the change in mission arose gradually. As the network grew to enormous scale it became difficult for any single person to grasp how it deployed to so many locations and altered practice.).

[39] *See, e.g.*, GREENSTEIN (2015), *supra* note 1, at Chapter 5 (providing additional details about the scaling of this network for private use with the addition of competitive and independent ISPs).

Broadly, those issues perennially raised tension in computer science research, since NSF's funding often had direct consequence for firms, and for workforce training in frontier technologies. The emphasis on "acceptable uses" also created a set of issues when NSF sought to "transfer" the internet to private industry for reasons numerous explained in this section.

It is well-known today, as it was in the late 1980s, that moving an operation out of government stewardship and into private hands can raise many issues. The acceptable use policies of NSF complicated the resolution of these issues because they limited the experience of users. That broad problem, in turn, undermined the ability of Steve Wolff, the manager of NSF's network from 1986 to 1995, as well as managers elsewhere who participated in the NSFNet, to forecast the appeal of new applications for users outside the university.[40]

To understand the problem, recognize that "technology transfer" can occur through a number of channels. The elevator pitch for technology transfer recognizes four distinct channels: giving away assets; licensing intellectual property; moving knowledge with moving people; and generating technological gains as part of procurement. The fourth channel had played an important role historically,[41] but only the first three played crucial roles during the transfer of the internet into private hands:[42]

1. *Give away technology.* In the case of tangible assets, governments can give its assets to private owners at no cost to the owners. In the case of software, it can place the code on a shareware site. In the case of new discovery, its researchers can explain the discovery in an academic journal accessible to anyone.

2. *Use a license.* Technology also can leave as part of a license for a fee, either exclusively for the highest bidder, or at a low charge to many licensees to encourage deployment. It can be protected in patents (and, occasionally, with copyright or related forms of formal intellectual property), and can be

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[40] *See* ABBATE, *supra* note 4, at 197 ("In 1990, NSF manager Stephen Wolff began discussing the idea of privatizing the internet with interested members of the internet community, holding workshops and soliciting comments from network experts, educational groups, and representatives of other government agencies.").

[41] *See* FLAMM, *supra* note 25 (documenting the importance of procurement for the development of computing in the 1950, 60s, 70s and part of the 80s, especially at the military and NASA). Arguably, the sentence in the text is an oversimplification, because procurement of the super computers and the services to build the internet during the NSF era of stewardship also played a crucial role in the internet's development.

[42] *See, e.g.*, ABBATE *supra* note 4; Abbate, *supra* note 20; GREENSTEIN (2015), *supra* note 1, at 72-80 (both explaining how if procurement played a role, it did so in the allocation of managerial responsibility for the NSF backbone, and arguably, in the bids to develop equipment for the internet).

licensed through actions typically governed at a university technology transfer office.

3.   *Move with people.* Technology can leave in someone's head. It can walk off the premises when a student graduates (e.g., sometimes with training that aides a private firm), or walk out the door when a professor or post doc leaves (e.g., sometimes to start a business, or take a job).

Why care about these channels? For one, the choice among these is NOT cost-neutral or revenue-neutral for self-interested firms who receive the benefits. Second, the resolution of the transfer also can have major consequence for the value of invention, in general, and for specific firms with market interests whose value depends on the government transfer, in particular. That leads to the third observation: when such transfers concern technologies with anticipated high value, the absence of good governance permits the transfer to become potentially sloppy, corrupt, and error-prone.[43] This leads to the biggest issue behind technology transfer: when a technology cannot explore many valuable applications (e.g. prototypes for electronic commerce) because it violates "acceptable use," how do administrators know in advance, which of the channels will lead to the highest value? Because "acceptable use" limit the use cases to guide them, they can make only educated guesses.

None of these observations are news (at a broad level) to experts in technology commercialization. They do, however, fall outside the conventional economic narrative, and provide a distinct set of lessons from the challenges facing those who sought to derive value from NSF internet. After more than two decades of government subsidized R&D, the decisions for transferring technology contained the potential to make those innovations more or less valuable to society. Governance of technology transfer had to play a crucial role. Again, appreciating these observations leads to distinct insights for policy that the conventional economic narrative would not generate.

Rather than take the reader through all the well-documented events, the discussion in this section provides several examples to illustrate the broad points. As with prior examples, the changing features of the internet further complicated these issues. By the late 1980s, the research-oriented internet had accumulated numerous capabilities affiliated with software to make it easier to use. Numerous advances accumulated, and, in particular, a set of

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[43] *See* LINDA COHEN & ROGER NOLL, THE TECHNOLOGY PORK BARREL 77-364 (1996) (developing this theme with extensive study of several examples of government subsidized technical inventions that crossed into commercial markets).

software improvements from Tim Berners-Lee altered the common experience just as privatization of the internet got underway. Berners-Lee created a viable system for hypertext that worked on top of the internet. Tim Berners-Lee worked for CERN, based in Switzerland. He innovated a form of hypertext, which he called the World Wide Web.[44]

At the time of privatization in the first half of the 1990s, the full scope of the web was unsettled. Even though later observers distinguish between the "web" and "the internet layer," such distinctions were less clear to contemporaries at the time those events took place. Indeed, Berners-Lee initially sought to get endorsement for his hypertext software from the Internet Engineering Task Force ("IETF"), and make it a standard part of internet protocols. Given the ambiguity, for the purposes of this discussion, the discussion will treat it all as part of the internet subsidized by government. This section's discussion also will take a similar approach to tools built directly on top of the web at the same time, such as the browser, the webserver, and the search engine.

B. *Giving Away Assets and Non-exclusivity*

The transfer of the internet to private hands succeeded in having a large economic impact, in part, because it escaped "exclusivity." That is, the process of privatization did not result in ownership and management of the backbone by a single organization who monopolized key assets. Instead, the backbone left government ownership in such a way to seed competitive carrier markets. While that might seem like an obvious public goal in retrospect, it was easier said than done. NSF did not possess regulatory authority to mandate actions common in other communications services–such as simple reporting requirements, or minimal geographic coverage–and, similarly, it did not have authority to compel actions that fostered competitive entry, nor could it levy fines for lack of compliance with rules. As it happened, the initial design of the privatization of the backbone, when first proposed by NSF, did not contain any mechanism to insure the rise of competitive markets.[45]

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[44] *See* GREENSTEIN (2015), *supra* note 1, at Chapter 4 (providing the full story). The Web is several inventions bundled together to give the user the experience of hypertext. Berners-Lee had convinced his supervisors the software had the potential to be useful for CERN. His first example was the office directory in hypertext, which was a use inside one organization. After making it available on shareware the most popular uses began to linking across organizations.

[45] *See generally* ABBATE, *supra* note 4, at 197, for further explanation. Steve Wolff's decision to privatize the backbone in itself illustrates another important lesson about governance. Wolff, the then-director of the NSFNET, recognized that there was no technical reason why the government had to operate the internet backbone. He asserted that private firms could provide

Summarizing a long set of events, when the U.S. government initially proposed to privatize the Internet backbone and related equipment, IBM, one of the providers of the NSFNET, tried to make a deal that removed any obligation to IBM for interconnecting with anybody prior to privatization, and, in addition, legally required that they not interconnect with any carrier carrying traffic that supported for-profit activity. IBM's lawyers tried to have the legal rules interpreted in such a way that IBM would have been the sole national backbone provider in the U.S. prior to the official moment NSF withdrew from owning the Internet backbone. From there, it aspired to disadvantage any potential rival and build its business into the dominant provider of backbone services after privatization.[46]

IBM almost succeeded, but ultimately failed after its efforts gained publicity and generated outrage. Eventually the Government Accounting Office and then-Congressman Rick Boucher, intervened to change NSF's charter to short-circuit the legal maneuvers of IBM's lawyers.[47] As that was happening, IBM's actions so angered other data carriers, it motivated several to establish the Computer Internet Exchange ("CIX"), which initiated the first data-sharing practices for competing carriers.[48] Along with the pressures placed on it, the CIX example, in turn, motivated NSF to redesign its privatization efforts, including data-sharing as part of its final plan. That plan fostered a competitive backbone industry at the outset of the transfer.

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services as efficiently, or more so, than government-managed sub-contractors. He initiated a series of steps aimed at what would be a transfer of technology out of exclusive government management and use. There is a broad lesson illustrated within this decision: when a technology reaches a point where private firms can operate it, the transfer does not necessarily happen on its own. It requires government managers who recognize this opportunity, and it may even require active nurturing from government officials, as it did in this case. As it happened here, Wolff had the support of the NSF's management, but he encountered considerable resistance from other internet stakeholders in the research community.

[46] *See* GREENSTEIN (2015), *supra* note 1, at Chapter 3 (providing a full rendition). *See also* Rajiv C. Shah & Jay P. Kesan, *Fool Us Once, Shame On You – Fool Us Twice, Shame on Us: What We Can Learn from The Privatizations of the Internet Backbone Network and the Domain Name System*, 79 WASH. U. L. REV. 89, 108, 113 (2001) (providing a different take on the events).

[47] *See* Segaller, *supra* note 35 (recounting partially Boucher's role in opening the internet to commercial use). *See also* Shah and Kesan, *supra* note 46, at 113-14 ("After the hearings, Congressman Boucher introduced a bill to remove the NSF's AUP. This bill was amended later to allow commercial use of the network as long as it would increase the networks' utility for research and education.").

[48] *See* GREENSTEIN (2015), *supra* note 1, at Chapters 3-5 (detailing how because of the NSF's "acceptable use" policy, there had been little experimentation with deploying the internet for commerce, and nothing related to exchanging data between otherwise competing firms. There also was little understanding about its cost structure outside of an academic environment. Relatedly, there was only experience with incentives to build routes for existing research institutions, and virtually none with entrepreneurial incentives building routes for new users, such as private users.).

The rise of a competitive backbone played an important role in creating value on the internet in the late 1990s, as it encouraged a competitive supply of access.[49]   To summarize, society was strangely fortunate that IBM attempted and failed to be the sole national backbone provider. Events would have differed had IBM succeeded, and NSF would not have planned for competitive data interchange had IBM not catalyzed others by making any attempt at all.[50]

C. *Conflicts Between Shareware and Ownership*

Another example of unexpected management challenges during technology transfer occurred outside the U.S. at the European Organization for Nuclear Research ("CERN") in the 1990s.[51] Not long after Berners-Lee made the World Wide Web available on shareware, he foresaw the need for a standards organization or consortium to govern the evolution of the protocols, and he approached the IETF for that purpose. Frustrated by the initial reception, and seeking to respond to some concerns about the property rights, he asked CERN to renounce any property rights on the World Wide Web. Management at CERN agreed, and in retrospect, it helped foster adoption of protocols by assuring users that no private firm would monopolize the direction of new protocol development.

Along with Berners-Lee's open practices, the lack of a single owner also fostered generativity in follow-up innovation. However, one must think about this properly: CERN's management agreed to give up property rights because of the parochial conflict with its mission, not because it was strategically anticipating how to foster technically-led economic growth.

The attitude of CERN's management turned out to be fateful for the web in one other respect – the location of a consortium to guide the Web. As it turned out, after several frustrating meetings at the IETF, Berners-Lee concluded he could not work with the IETF, and would need to establish a standards-oriented organization, which he would lead. CERN's managers were clear, however, that such a consortium or standards organization fell outside their mission, and CERN would not house such an effort. Berners-Lee eventually moved to MIT in 1994, where the model of a consortium was

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[49] *See* GREENSTEIN (2015), *supra* note 1, at Chapters 4 and 5 (providing the description of the rise of competitive carrier industry).

[50] *See* GREENSTEIN (2015), *supra* note 1, at 80-90 (providing the full story and linking IBM to the creation of CIX and the revision of the NSF privatization plan).

[51] This example also serves as a counterexample to the tendency to believe all inventions came from within the U.S.

well known. There he established the World Wide Web Consortium, and it still resides there today.

Reiterating, the organization that subsequently governed the most important software invention of the 1990s, could not, and did not, settle in the heart of Europe because managers at CERN did not expand their mission's scope beyond its parochial outlook. The institutional practices and flexible outlook of the US research community attracted the software designer to the US.

D. *Conflicts Between Licensing and Increasing Adoption*

Mosaic first appeared at the National Center for Supercomputing Applications (NCSA) at the University of Illinois in 1992, with funding from NSF for NCSA. While others had invented browsers, the core team at NCSA, principally Mark Andreesen and Eric Bina, gained permission to imitate and improve upon these browsers with many new features. They also developed server software to facilitate wider use. This project was just one of many projects at the NCSA, and arguably, not NCSA's most important project when first proposed. It quickly grew into an ambitious and imaginative attempt to help students use the web.[52]

Widespread adoption in 1993-94 led the University of Illinois to initiate a program to foster private use. While the University showed flexibility and administrative agility in fostering such use, it ended up making inconsistent policy.

Initially following standard practices at many universities, the licensing offices claimed ownership of the software (under Baye-Dole) and began a licensing program. This program upset Andreesen, who was offered a job as part of the efforts to grow and maintain the software after he graduated in December, 1993. He left Illinois for the West Coast, and returned in April 1994 with Jim Clark to recruit all the key programmers, who, days later, left the University and started their own firm, Mosaic Communications Company ("MCC"). Perhaps the programmers would have left in any event, but it is fair to say they did not leave on good terms.

By this point, the University, through an intermediary, had begun to license Mosaic. Eventually more than a hundred firms signed up under this license program. That intermediary sued MCC for violation of copyright

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[52] For the story of the development of the browser, *see* GREENSTEIN (2015), *supra* note 1, at Chapter 4 (explaining that the browser was necessarily an unexpected invention). The web had not yet grown at the time of the founding of NCSA. It would have taken uncommon prescience to anticipate such an application, and the NSF (sagely) had policies in place to permit such developments.

due to the use of the name "Mosaic." In response, MCC changed their name to Netscape. This was consistent with its earlier decisions not to use existing code, and to program their browser from scratch, so as to avoid any intellectual property claims from the same intermediary. While this tussle over a name had little commercial consequence, the founders of Netscape, already on bad terms with the university's leadership, had little positive to say in public about their alma mater. The legal tussle over copyright made little difference, but, ironically, that may have been to society's benefit. Netscape soon became a catalyst for significant economic changes. Had the lawsuit slowed down Netscape in a significant way, would it have had as much impact? There is no way to know.

Later events made matters even more ambiguous. The intermediary eventually licensed the software to Microsoft in January of 1995. Microsoft became the final licensee, and, to the surprise of no analyst following the industry, in a few months Microsoft's actions rendered the actions of the other hundred licensees as valueless. In a few months more, Microsoft began to compete with the firm founded by the University's own students.

Cataloguing the inconsistencies would take pages, but a simple summary will do here. Money and diffusion both motivated the university, but did not work in the same direction. Money potentially had little to do with the university's mission to diffuse invention to participants in society and to society's benefit. After settling a lawsuit, the university's licensing deal with Microsoft netted the university more than twenty million dollars. While large for the university, and helpful in negotiating with state legislative oversight committees in Springfield, Illinois, it was a pittance in comparison to the private strategic value at Microsoft, which, arguably, ran at least to the hundreds of millions.[53] The value to society from diffusion of the browser was even higher. Should the university have negotiated a better contract, or did it meet its mission by negotiating with major adopter? To be clear, there was no easy answer to the inherent conflicts between actions that support diffusion, societal impact, and money-making.

Neglected during the ensuing ruckus, the server software, which was necessary to make the browser useful, laid on University shareware sites in late 1994 and early 1995. The NCSA did not attempt to license it, and, for all intent and purposes, neglected managing it for almost a year. Private

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[53] *See* GREENSTEIN (2015), *supra* note 1, at Chapter 4 and 11 (providing the full explanations about the creation of the browser and the subsequent "browser wars.") The license saved Microsoft time. The strategic value from that was large, though calculating a precise monetary value to this strategic gain would be virtually impossible. The irrefutable evidence of the benefit to those months was the priority the CEO placed on the project, and the enormous resources Microsoft would devote to "catching up with Netscape."

server web masters became frustrated, and eventually took matters into their own hands, developing improvements to meet their private needs. By the time the university hired a new person to steward the server software, the users had formed an open source organization, Apache, and embarked on a journey to becoming the most commonly used web server software in the world. Recognizing that the situation had escaped their control, the university wisely chose not to take any further action, and instructed their new webmaster to stop. Ironically, the university's neglect helped society adopt and make good use of the product.

E. *Licensing with Different Conceptions About Value*

As another example of the ways transfer policies can change the value of technology, this next example chronicles the efforts of Larry Page, who proposed an algorithm, later called Page-Rank. Page and classmate Sergey Brin implemented this algorithm in the summer of 1995. Notably, the original grant application to NSF, which funded Page's work for his advisor, and awarded by NSF in 1994, did not promise anything like Page-Rank, or any other specific or general indexing tool for the Web. The grant aimed at developing tools for digital libraries. Fortunately for society, NSF had policies that permitted grantees to respond to new opportunities, and, wisely, did not literally bind Page's and Brin's advisors to the precise scope of promises in their NSF application for funding.[54]

Stanford (under Baye-Dole) obtained a patent for Page-Rank, and, following standard practice, tried to find licensees. The licensing office could not find anybody in the Valley to take the deal, including the most high-profile firms at the time.[55] Frustrated with the response but encouraged by positive experiences with a prototype widely used on campus, Brin and Page decided to (temporarily at first) quit their dissertation writing, and, instead,

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[54] That has not deterred NSF from boasting about funding this researcher. *See* GREENSTEIN (2015), *supra* note 1, at 365-371 (explaining that NSF justifiably lists Google's search engine as a product of federal research, but that misses interesting historical circumstances which led to its creation, which nobody ever promised to NSF and was not formally required by NSF as part of their grant).

[55] *See* GREENSTEIN (2015), *supra* note 1, at 365-371 (detailing how there has been a lot of Monday morning quarterbacking about why this deal did not occur). Arguably, Stanford asked for too much money, and/or it approached firms who did not appreciate the significance of the inventions. Was there any price at which a deal could have resulted? Did the management appreciate what the patent contained? Complicating this discussion further, another patent, developed by a graduate student at Cornell and taken out at roughly the same time, covers many similar inventions. For a number of reasons, he concluded that developing a business in the U.S. was not possible. He moved home to China, and began the firm, Baidu, which became the largest search engine in China.

started a new business in 1998, which they named Google. One thing led to another, and they never returned to finish writing their dissertations, which would have led to their PhDs.

Which channel would have made society better off? This example used both licensing and human mobility, and the latter became the channel to accomplish what the licensing did not accomplish. Google's search engine eventually changed the world. Today, Google is the third most valuable business on the planet. Had the university's licensing program succeeded, Page and Brin would not have founded their firm, and society might not have seen the growth of Google, or anything similar. That certainly would be a different world than today.

Summarizing the broad point across all the episodes, all of these episodes illustrate ways in which the value of technology depended on the governance of the transfer of technology from universities to private hands. The governance shaped the realized value, either by settling conflicts when one channel came into conflict with another, or by determining outcomes when unexpected events altered the perceived value of using one of those channels. More broadly, with money on the line, these transfers were not easy to govern, the economic tradeoffs were non-obvious in advance, and unintended consequences determined salient features of the outcomes. Governance of technology transfer had to play a role. It was unavoidable.

Summarizing the forward-looking lessons is challenging, because these episodes do not collectively generate a general solution to policy conflicts when universities or not-for-profit laboratories seek to transfer technology. It was (and still is) quite difficult to articulate general solutions for technology transfer policy in advance of events. That does, however, suggest several principles for forward looking technology policy in such situations. One observation is obvious: all these episodes suggest the need for managerial humility in the face of the unknown, and contingent planning for agile policy actions in the face of the unexpected. In addition, these examples suggest that the situations with the highest value encountered issues when they adopted routine processes for incremental technical inventions (with less value at stake), and failed to anticipated and/or adjust and adapt to the inconsistencies of the policies that emerged due to the high stakes. Moreover, real time decision making had enormous value in each of these episodes, so good outcomes depended crucially on the intervention of many "honest policy wonks," who showed good judgment at just the right moment.[56]

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[56] *See* GREENSTEIN (2015), *supra* note 1, at Chapters 2-5 (providing extensive discussion about the role of "honest policy wonks" from which this conclusion emerges).

Finally, it is worthwhile to reiterate the broader point. The conventional narrative neglects technology transfer, its governance, and the inevitable impact of the decisions during the transfer from public to private hands. That suggests the conventional narrative is grossly misleading to imply that invention alone is sufficient for creating value. Transfers played a crucial role in creating value from the internet, and surely will play a crucial role in the creation of value for any sufficiently ambitious program to subsidize invention. Moreover, such technology programs must play an inevitable and crucial role when the value arises from unexpected applications of technologies developed under a mission-orientation, because such settings necessarily need explicit efforts to deploy inventions to users other than the earliest users. The conventional economic narrative offers too sanguine and too incomplete a view of government sponsored R&D in these circumstances.

CONCLUSION

While the conventional economic narrative remains consistent with invention of the internet, this essay shows why that narrative provides incomplete insight into several crucial features of the experience. To understand how government created the internet, and why the experience created such high value, an analyst needs more than the conventional economic narrative. An analyst needs to appreciate the role of lead-users and good governance of technology transfer.

These insights have several far-reaching implications for forward-looking technology policy. For one, these observations suggest that supporting invention and prototyping with only money–*sans* any policy for deployment–may not be sufficient for nurturing useful early stage use of government-sponsored R&D. Deployment and learning from operations may be required to motivate further invention. In addition, while the government can act as a lead user in areas that touch on government functions, such as the military, the value of that learning for non-government users may or may not play any role in funding decisions. It may be necessary to pass stewardship to non-governmental owners to generate learning about new uses, and to assess the relevant needs of non-governmental users. Once again, there must be policies for transferring this learning in order to gain the full value from government-sponsored R&D.

It is worthwhile to conclude with a note about government actions in creating and subsidizing innovation, with considerable attention paid to defense. This essay suggests value depends on many factors over which the military has little control, and potentially even less interest. Will passing some technologies into private hands create economic value? It is hard to say

that it will in any given situation, but in the absence of good governance, it probably will not. That is not an assuring conclusion. Even if the R&D succeeds in creating breakthrough technologies, the value from decades of federal investment depends on whether some "honest policy wonk" shows good judgment at the right moment.

As the conventional economic narrative would counsel, future risks are not a reason to defer from undertaking inventive projects, as the government can manage risks with a proper portfolio, and can internalize the gains from the otherwise diffuse benefits enjoyed after the inventions. Rather, this essay contains a set of cautionary lessons that point in a different direction. Events can and do stray outside the conventional economic narrative, and that can and does shape the level of economic value from the technology's private use. Such straying occurred in the canonical case of the Internet. If it happened there, it surely will happen elsewhere. This means it will be challenging to, once again, recreate high-impact technological inventions with government subsidies for R&D. It also means the likelihood of experiencing a good outcome will rise with appropriate investments in policy instead of their neglect. Most of all, a good outcome arises from government actors' co-investment in administrative processes and policies to nurture the creation of technically-enabled economic value.