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Introduction

Adam B. Jaffe and Benjamin F. Jones

With the 1945 publication of *Science: The Endless Frontier*, Vannevar Bush established an intellectual architecture that helped define a set of public science institutions that were dramatically different from those that came before. Yet what was radical in 1945 remains largely in place today. At the start of the twenty-first century, many aspects of the science and innovation system—from its organization and scale to the role of geography and the nature of entrepreneurship—have witnessed important changes, with potentially substantial implications for the design of science policy and institutions both today and in the decades ahead.

This volume explores two overarching questions: What are critical dimensions of change in science and innovation systems? and What are the implications of these changes for policies and institutions in the twenty-first century? In this introduction, we present an overview of eleven new contributions that explore important dimensions of these questions.

Part I of the volume investigates the organization of scientific research, especially new norms around collaboration, which appears to be a central force reshaping the production of knowledge. These studies also lay some important foundations for part II, which considers shifts in the geography of scientific research and connects to a broader literature suggesting that geographic agglomeration remains an enduring and, in some ways, strength-

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ening feature of innovative activity. Part III considers modern modes of entrepreneurship and market-based innovation, with chapters studying mobile applications, clean energy, and state-level entrepreneurship policies. Finally, in part IV, our contributors investigate changes in science institutions and science-innovation linkages within broader historical visions, including from the perspective of *Science: The Endless Frontier* itself.

The following sections discuss each of the volume's chapters, with the purpose of presenting key findings while drawing out common themes and potential policy implications. In a concluding section, we summarize the broad, fundamental changes these contributions inform and point to additional aspects of the science and innovation system that may be undergoing substantial shifts but remain for future study.

The Organization of Scientific Research

A primary theme, featured in four different contributions to this volume, considers the evolving role of collaboration in science—within institutions, across institutions, and through the scientific community as a whole. These contributions build primarily on two theories for increased collaboration in the sciences, both of which increase the return to collaboration. One theory emphasizes the benefits of increased collaboration as individual researchers become increasingly specialized. This tendency can be seen as a necessary response to the rising "burden of knowledge" as the stock of knowledge accumulates and the individual knows an increasingly narrow fraction of it (Jones 2009). The second theory emphasizes the declining costs of collaboration through the advance of information and communications technologies (Agrawal and Goldfarb 2008). An observation that persists across the contributions of this volume and elsewhere (Kim, Morse, and Zingales 2009; Agrawal, Goldfarb, and Teodoridis 2013) is that both forces appear to be operating. The following contributions add substantial and novel evidence to these dimensions, while also extending conceptions of collaboration in the organization of scientific research.

In "Why and Wherefore of Increased Scientific Collaboration," Richard B. Freeman, Ina Ganguli, and Raviv Murciano-Goroff establish several new facts about scientific collaborations, comparing colocated coauthors, geographically distant coauthors within the United States, and coauthors across countries. Freeman et al. study nanotechnology, subfields of biomedicine, and subfields of physics. An important innovation of this chapter is to conduct in-depth surveys of the authors, rather than relying purely on bibliometric databases; the surveys produce first-order, novel insights about the various collaborations.

One striking finding is that nearly all geographically distant coauthors were once colocated. Typically these distant coauthors were previously colocated either as colleagues, as visitors, or in an advisor-student relationship. These findings extend a body of work establishing that face-to-face interaction appears valuable even as communication technologies advance (e.g., Olson and Olson 2003; Olson, Zimmerman, and Bos 2008). A second finding is that the most common reason for collaboration, whether domestic or international, is access to specialized human capital, which is consistent with the burden of knowledge view of the demand for collaboration. Collaborations motivated by access to physical equipment or grant funding are, by comparison, less common.

In "The (Changing) Knowledge Production Function: Evidence from the MIT Department of Biology for 1970–2000," Annamaria Conti and Christopher C. Liu provide a rich and textured analysis of changes in scientific production by focusing on a leading biology department. The authors establish that later cohorts of students experience longer training periods, longer periods until the publication of their first paper, fewer first-author publications, and, consistent with much other literature, more coauthors per paper. The life cycle effects are consistent with the extended training phases associated with a rising burden of knowledge (Jones 2010), while the extended training period is also consistent with a declining number of future positions per student in biomedicine (Stephan 2012). Regardless, as the authors discuss, the incentive for entering biomedical careers may be decreasing; a striking fact in their data is that the length of training, including graduate and postdoctoral work, now exceeds ten years—a long road that may dissuade entry into these scientific careers.

Ajay Agrawal, John McHale, and Alexander Oettl, in "Collaboration, Stars, and the Changing Organization of Science: Evidence from Evolutionary Biology," examine how the locus of top research in evolutionary biology has changed with time. The chapter presents two intriguing and seemingly contradictory facts: the concentration of quality-weighted research produced by the top 20 percent of university departments is decreasing with time, yet the concentration of quality-weighted research produced by the top 20 percent of individual scientists is increasing with time. To reconcile these contrasting trends, the authors suggest that rising collaboration is a natural mechanism. In particular, the decline in the costs of distant collaboration, via advances in information and computing technology, may better connect lower-tier research departments to top researchers. A more specific mechanism may be the increasing capacity of star researchers to maintain collaborative relationships with their students once their students move away. More generally, the theme where information technology can link geographically distant players to centers of research excellence (here, stars) is repeated in various forms below—see the contributions of Branstetter, Li, and Veloso (chapter 5) and Forman, Goldfarb, and Greenstein (chapter 6).

In "Credit History: The Changing Nature of Scientific Credit," Joshua S. Gans and Fiona Murray explore collaboration in a broader frame, emphasizing that collaborations also occur across papers in the community of scholars pushing forward a scientific field. This notion, which is strongly grounded in the cumulative nature of innovation, emphasizes that scientific collaboration often proceeds through mechanisms other than the coauthor-based organizational form of a single paper. Taking classic Mertonian conceptions of scientific norms, this chapter then argues that the organizational form of collaboration that scientists take naturally hinges on credit considerations. On one dimension, credit considerations may influence coauthorship choices—both whether and with whom to coauthor. Moreover, the decision of when to call research "complete" and publish it, rather than continuing on one's own in private, may also naturally hinge on how credit is given when others build on the initial work. Thus both the unit of common analysis—the paper itself—and its coauthorship arrangement may be endogenous to credit considerations, and in important ways.

This chapter reviews collaborative choices under this broader frame, animates these choices with compelling examples that illuminate the diversity of organizational forms and concerns over credit, and provides a formal model to synthesize the analysis. The model develops conditions under which an author may "integrate" (keep their initial research results private in pursuit of gaining credit for a larger cumulative contribution), "collaborate" (draw in coauthors to improve the research potential), or "publish" (disclose the early results and gain credit as others build on the findings). The model thus links knowledge accumulation, collaboration, and credit sharing to inform many credit-related issues. Applications include the "salami slicing" of results into small, publishable pieces and the potential divergence between equilibrium organizational forms and the social optimum; for example, if peers assign excessive joint credit to coauthored research, then credit considerations will lead scientists to coauthor too much. More generally, this chapter nicely integrates credit considerations into research on collaboration and outlines a compelling and rich agenda for further work.

The Geography of Innovation

The geography of innovation has also undergone substantial changes. Three large forces appear to be at work. First, economic development has led many countries to catch up to the world technology frontier, introducing new players onto the global science and innovation landscape. Second, the advance of information and communication technologies has allowed people at geographically distant points to interact more easily in the production and consumption of new ideas. This force has led some observers to declare a "death of distance" (Cairncross 1997) or that the "world is flat" (Friedman 2005), with possible fundamental implications for economic geography. Third, and in contrast to the last forces, increased specialization of human capital or other inputs may encourage further geographic agglomeration. This force, which can link burden of knowledge reasoning (driving increasing specialization) with a classic Marshallian analysis of geographic agglomeration, suggests that the primacy of place (e.g., in Silicon Valley or other clusters) may increase with time rather than dissolve.

The policy implications of these forces are substantial. Should regions increasingly pluck the fruit of research insights produced elsewhere, local taxation to support such public goods may be more difficult to sustain politically. Meanwhile, local investments to promote innovative clusters, often attempted by polities seeking to replicate other region's successes, may be either more or less well motivated or sustainable depending on the balance of the above forces.

This section considers two valuable contributions that speak to these issues. In "The Rise of International Coinvention," Lee Branstetter, Guangwei Li, and Francisco Veloso examine the explosion of patenting from inventors in China and India. They start by noting a puzzle: both countries appear to have remarkably high patenting rates despite low per-capita income, which appears to contradict a basic idea of economic development where developing countries grow primarily through capital accumulation and the adoption of existing technologies, rather than through the innovation of new technologies. In Branstetter and colleague's contribution, the puzzle is resolved through two kinds of empirical analysis. First, studying patents issued in the United States by Chinese and Indian inventors, they find the vast majority of patents coming from these developing countries occur through multinational corporations. Moreover, these patents typically involved collaborations between inventors located in China or India and inventors located in advanced economies. One implication is that the rise in patenting by China and India may not be undermining the technological leadership of advanced economies and their multinational corporations, but rather assisting it.

While these results are based on patents issued in the United States (which are presumably the inventions with more substantial global value), this chapter also provides a detailed assessment of patents issued domestically in China by the State Intellectual Property Office (SIPO). China's domestic patent rates have recently soared, which has suggested to some observers that domestic Chinese firms have become highly innovative. However, Branstetter, Li, and Veloso find that only 20 percent of these SIPO patents qualify as patents in the usual sense (being new and useful, and evaluated as such). Moreover, half of these patents are already filed in foreign jurisdictions and are simply seeking protection in China. Among the remainder, many come from multinational subsidiaries.

This chapter thus takes an especially deep look at the first force for geographic change noted above by studying the entry of newly developing countries onto the innovation landscape. The chapter finds that China and India neither overturn conventional wisdom about the development process nor suggest much innovation independent from multinational enterprises. At the same time, these countries are increasingly connected through collaboration into multinational research and development (R&D) efforts, suggesting a dimension on which the world has become flatter, but in dependence with global collaboration.

In "Information Technology and the Distribution of Inventive Activity," Chris Forman, Avi Goldfarb, and Shane Greenstein turn the geographic lens to the concentration of patenting within the United States and explore linkages between geography and information technology. Studying patenting at the county level, they find that counties saw larger patenting growth rates when they were both patenting laggards in 1990 but Internet adoption leaders in 2000. Echoing the prior study, the authors also find some evidence that it is distant collaboration in the context of multiestablishment firms, rather than purely local innovation, that information technologies appear to assist.

Nonetheless, despite this evidence, a primary finding of Forman and colleagues is that the overall geographic concentration of patenting activity has substantially increased with time. While the rate of patenting increased 27 percent over their study period (1990–2005), it increased 50 percent among the initial top quartile of patenting counties. In initially below-median counties, patent rates did not grow.

This chapter comes close to an explicit analysis of the contest between second and third forces noted above, with emphasis on measuring overall concentration trends while explicitly accounting for variation in access to information and communication technologies. Increasing concentration appears to win out, suggesting the dominance of some version of the third force, while information technologies somewhat soften the concentration tendency. Overall, these chapters paint a picture where concentration appears to be increasing, and any tendency for a death of distance occurs primarily through collaboration with the agglomerated regions. From a policy perspective, these findings suggest that the presumption of substantially "local" gains may be a surprisingly durable basis for public R&D support, both in the robustness of clusters and the dominance of advanced economies, or at least their multinationals, in the invention process.

Entrepreneurship and Market-Based Innovation

The words "entrepreneur" and "entrepreneurship" do not appear in *The Endless Frontier*. Today, many analysts of the science/innovation system see them as crucial to reaping the potential social and economic rewards of the public investment in science. While other National Bureau of Economic Research (NBER) volumes have been devoted to the role of entrepreneurship in this system, in this volume we have two chapters that focus on entrepreneurship in specific emerging sectors (renewable energy and mobile applications software), and one that looks at the history of the "policy innovation" of state-level programs designed to foster local/regional innovation and entrepreneurship.

Ramana Nanda, Ken Younge, and Lee Fleming explore the nature of the patents of venture capital-backed firms in the renewable energy sector in "Innovation and Entrepreneurship in Renewable Energy." Given climate change challenges and the role that venture capital-backed firms have played in biotechnology and information technology, this chapter examines VC's role in the renewable energy sector. Using a new data set of the renewable energy patents of both VC-backed and incumbent firms, the authors find that most such patents still come from incumbent firms. However, patents from VC-backed firms are more novel (defined by a measure derived from textual analysis of patent claims) and have greater technological impact (based on the number of later citations to the patent from subsequent patents) than those of incumbent firms. The authors also show that a surge of VC funding in this sector early in the first decade of the twenty-first century was associated with an increase in patenting by start-ups. Finally, the chapter discusses structural aspects of this sector that may limit the ability of venture capital to provide the support needed if rapid technological improvement is a policy goal.

In "Economic Value Creation in Mobile Applications," Timothy F. Bresnahan, Jason P. Davis, and Pai-Ling Yin characterize the state of innovation and entrepreneurship in a new sector: mobile software applications. The authors note that in just a few years the installed base of mobile devices already vastly exceeds that of any other programmable device; this large base combined with the ease of entry into the two mobile programming platforms (iOS and Android) has allowed three-quarters of a million programming innovations (apps) to be created. The chapter proceeds to analyze the ways in which this innovation wave resembles and differs from previous waves. The authors note the tremendous importance of the last step in the chain from technical discovery to creation of economic value, whereby creating new markets may itself require innovations that are distinct from the technological ones. The scale of the mobile sector is qualitatively greater than we have seen before, with market-dominant personal computer (PC) applications such as the spreadsheet having emerged when the quantity of software created for that platform numbered in the hundreds rather than the hundreds of thousands already in existence for mobile. The authors argue that this vastly greater scale creates a bottleneck whereby a new app and the subset of potential customers who might use it have trouble finding each other. Currently, existing firms (e.g., Starbucks or airline companies) have been most successful at solving this problem in mobile apps because they start with an existing customer base, but it remains to be seen what market mechanisms will evolve in the future and what firms will be most successful with those mechanisms.

If *The Endless Frontier* launched science and innovation as a central concern of the federal government, it was several decades before states began to consider their own policy choices. Maryann Feldman and Lauren Lanahan describe the emergence and evolution of state-level interventions in "State Science Policy Experiments." On one level, states invest in science and innovation for the same reason as the federal government, to create public goods and derive the spillover benefits therefrom. But this raises the obvious question of why states would not just leave this to the federal government and enjoy the benefits within their borders without having to invest their own resources. The answer, of course, is that the spillovers may be partially localized, so that states invest to increase local innovation and local economic growth. This chapter looks at the factors affecting states' adoption of the three main categories of state programs: "eminent scholars," designed to attract scientific talent to the state; "centers of excellence," designed to build research expertise that involves industry; and "university research grants," which provide funding for specific research projects. The results indicate that eminent scholar and university research grant programs seem to build on existing strengths in research, while the centers of excellence seem motivated by more generic economic growth concerns.

Given the apparent durability of geographic agglomeration in anchoring innovation (see the above section on geography and innovation), state-level policies may arguably be quite fruitful in bringing local benefits if these policies are well designed. The Feldman and Lanahan analysis thus appears to push forward an important research agenda. State policy to encourage innovation is widespread and expanding, thus calling for a detailed assessment of its effectiveness, especially given the variety of policy approaches states can undertake.

These chapters speak to entrepreneurship but more generally speak to market-based innovation and its potential interfaces with policy. If Bush's vision in *The Endless Frontier* centered on a robust public commitment to R&D, and the postwar period initially saw enormous growth in public R&D expenditure, the story since the early 1960s has been quite different, where private sector R&D funding has grown much faster than public funding.[1] The above chapters suggest specific mechanisms—including the roles of venture capital and platform formation—that go beyond the vision of Bush and appear to be central features of the modern innovation system. The role of standard setting, which can be assisted by public institutions, and market-based innovation policies such as the R&E tax credit and the tax treatment of early stage finance may then be increasingly important policy levers to encourage innovation, suggesting a broader and retuned vision from the emphasis on basic science that Bush articulated. We further take up these themes below, where the next two contributions consider the reali-

1. For example, in 1960 US federal government R&D funding and US private sector R&D funding were nearly 2 percent and 1 percent of GDP, respectively. By 2000, these shares had reversed. (See the National Science Foundation Science and Engineering Indicators 2012 at http://www.nsf.gov/statistics/seind12/).

zation and limits to Bush's vision and the shifting technology paradigms that may help define where innovation occurs.

Historical Perspectives on Science Institutions and Paradigms

The changes in science over the last half century encompass institutional evolutions as Bush's vision came to be implemented and also evolutions in the science-innovation paradigm itself as the types of technologies driving economic progress have evolved. Two chapters in this volume confront these central historical developments in the science and innovation system and offer rich, novel, and intriguing assessments of such changes. This volume closes with these broader historical analyses.

In "The Endless Frontier: Reaping What Bush Sowed?" Paula Stephan compares the current state of the basic research system with the vision that Bush originally articulated. On the surface we got what Bush wanted: a large basic research enterprise, centered in the university system, and funded by the federal government. But the system differs in some important ways from that envisioned by Bush, and Stephan argues that these differences are connected to a number of problems or issues in the existing system. First, the dependence on federal research funds for academic year salaries and the investments in buildings and equipment universities have made in order to compete for federal research funds have made universities dependent on a perpetually growing funding pie that no longer seems likely to grow at the same rate. Second, Bush envisioned research funded by research grants, while the building of human capital would be funded by fellowship programs. But today the salaries of PhD students and postdoctoral scholars are paid largely out of research grants. The result is that the size of education and training programs is determined not by the number of positions available for graduates, but by the needs of existing research labs for research staff. Such a system can operate in balance if the total research funding grows continuously, but creates another source of system instability as research funding remains flat. Third, perhaps as a result of the funding pressure created when a system built for growth confronts static funding levels, the need for public funding to facilitate high-risk breakthrough research seems to be giving way to a demand for incremental projects with a higher likelihood of success. Finally, while Bush envisioned a public investment in research that would be something like one-third medical and biosciences and two-thirds physical sciences, the political process that determines funding allocation has instead consistently devoted more than half of the federal research resources to biomedical sciences.

A second chapter providing a broad historical analysis argues that the scientific frontier discussed by Bush was not, in fact, endless, but was rather one in a succession of frontiers that sometime around the millennium was replaced by the "algorithmic frontier." "Algorithms and the Changing Frontier," by Hezekiah Agwara, Philip Auerswald, and Brian Higginbotham, argues that while the defining attribute of the world technological frontier in the mid-twentieth century was the application of science to product and process innovation, the current defining feature of the technological frontier is the ever-improving connections and interoperability among firm-level production algorithms, which are in turn made possible by the adoption of standards. Just as the transition from the industrial frontier of the nineteenth century to the scientific frontier of the late twentieth century meant that economists needed new analytical tools such as the knowledge production function and endogenous growth models, economists are now embarking on the development of new tools to understand algorithm-based innovation and growth.

An implication of this chapter is to emphasize that standard-setting institutions, in addition to basic science institutions, may be crucial for encouraging technological progress both today and in the decades ahead. Standard setting, like research and development, happens through both private sector and public sector mechanisms. To the extent that Agwara, Auerswald, and Higginbotham's analysis is accurate, research to improve standard-setting mechanisms becomes an increasingly impactful area of study. One may look no further than the recent development of mobile operating standards like iOS and Android to see an example of standards knitting together downstream demand and encouraging massive innovation and entrepreneurship in software applications—as detailed in Bresnahan, Davis, and Yin (chapter 8).

Concluding Comments

In July 1945, when Vannevar Bush wrote *Science: The Endless Frontier*, the world's scientific enterprise was a tiny fraction of its current scale. By articulating a compelling case for the impact of science and the need of public support (the first two sections of his introduction are entitled "Scientific Progress is Essential" and "Science is a Proper Concern of Government"), he helped set the United States, and ultimately many other countries, on a path toward strong and well-funded institutions of science, centered on universities and government labs, which can provide basic research insights and/or develop scientific human capital. Both of these outputs—ideas and people—Bush saw as the primary and essential way in which government can support industrial R&D.

Now we approach the seventieth anniversary of his seminal work and Bush's ensuing efforts within the government to create the modern science architecture. It is clear, based on the analysis in this volume, that major changes in the nature of science and innovation have occurred. One fundamental shift has occurred in the organization of scientific research. At a microlevel the shift toward collaboration, and the increasingly long period of PhD and postdoctoral study before researchers establish their own labs, impacts the scientific workforce considerations that center in the Bush vision. As articulated by both Paula Stephan and Conti and Liu, the system of human capital formation appears increasingly arduous, with a funding system that may redirect students from efficient skill building to faculty research needs. If the burden of knowledge is raising human capital demands on scientists, efficient training may be increasingly important; yet, as Stephan argues, our training systems may be pushing the other way. The shift toward collaboration also suggests a shift in the character of training, where learning collaborative and management skills may become an increasingly high-return investment, ultimately in furtherance of the individual's career and the overall science enterprise.

The shifts in organization, especially in collaboration, also link to shifts in the geography of innovation. Vannevar Bush wrote at a time when the United States sat uniquely as the only advanced economy left largely undamaged by war. It is not surprising that issues of the geography of innovation did not feature in *Endless Frontier*, while it is also not surprising that in today's globalized economy they are central to science and innovation policy debates. As discussed above, the chapters in this volume add to other recent empirical evidence (e.g., Glaeser and Kerr 2009; Puga 2010; Glaeser 2010) that suggests agglomeration economies remain a profoundly important aspect of innovation geography. The world may be getting flatter with respect to tasks that depend on codified knowledge and that can therefore be made routine, but fundamentally creative processes such as innovation appear to remain dependent on complex interactions among people that are facilitated by geographic concentration. While important aspects of geography—where distant researchers are increasingly connected, especially those who were once colocated—flattens the world in some respects, it appears that agglomerative tendencies continue to be strong, suggesting that local spillovers may remain a potentially credible basis for motivating a polity to bear costs in pursuit of science and innovation's public goods.

It seems plausible to imagine that a major force compelling Bush's vision of the long-run benefits of public science was the contributions that technologies such as radar, aircraft, and the atomic bomb had made to the war effort. These are examples of science harnessed for social goals essentially outside of the market system. But today our innovation goals—even those greatly enmeshed in public policy such as environment and health—are typically met by bringing products and processes to the marketplace successfully. Moreover, the private sector is the increasingly dominant source of R&D funding in the United States. This means that issues of market behavior and institutions, such as entrepreneurship and standard setting, play a significant role in the success of the overall system in delivering ultimate social and economic benefits from scientific research. From a policy perspective, these issues raise many possibilities for market failure. The chapters in this volume on innovation and entrepreneurship in clean energy and mobile applications, and on state science/innovation programs, illuminate important aspects of these issues.

Other issues, not studied here, suggest further substantial changes in the science and innovation system. The university-market interface has evolved, especially with the Bayh-Dole Act, the rise of technology transfer offices, and the interest of nonprofit research institutions in both creating and tapping royalty streams. Intellectual property regimes including patenting, copyright, and even noncompete agreements, have experienced changes in their strength, scale, and strategic use through evolutions of law, court interpretation, and with the rise of new types of codified knowledge, like software and gene sequences, that challenge standing intellectual property systems. Constraints imposed on the basis of social ethics, too, have evolved, with more oversight and restrictions upon human experimentation, especially through institutional review boards, even as ever-expanding consumer data resources are unleashing new innovative opportunities in the private sector, often at the expense of consumer privacy. These subjects and others are also worthy of substantial consideration in any holistic assessment of the "changing frontier." What is clear is that science and innovation landscape has undergone profound transformations since Vannevar Bush shaped the US science institutions based on the landscape he observed.

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