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The evolution of science-based business: innovating how we innovate

Gary P. Pisano*

Science has long been connected to innovation and to business. As early as the late 19th century, chemical companies, realizing the commercial potential of science, created the first industrial research laboratories. During much of the 20th century, large-scale business enterprises like DuPont, GE, Westinghouse, IBM, Kodak, Xerox (PARC), and AT&T (Bell Laboratories) created in-house labs capable of first-rate basic scientific research. In recent decades, however, the connection between science and business has begun to change in important ways. While the corporate lab declined, new "science-based businesses" in sectors like biotech, nanotech, and energy emerged. Universities also became active players in the commercialization of science. In short, science has become a business. This essay examines the institutional and organizational challenges created by this convergence of science and business through a Chandlerian lens. It highlights three fundamental challenges of science-based businesses: (i) managing and rewarding long-term risk, (ii) integrating across technical disciplines, and (iii) learning. Whereas these challenges were once managed inside the boundaries of corporate R&D labs—under the auspices of Chandler's visible hand—today the invisible hand of markets increasingly governs them. An assessment of this form of governance against the requirements of science-based businesses suggests a gap and a need for organizational innovation.

1. Introduction

Alfred Chandler taught us that organizational innovation and technological innovation are equal partners in the process of economic growth. Indeed, one often requires the other. In the late 19th and early 20th century, the large-scale modern corporation both shaped and was shaped by advances in electrification, mass production, and transportation (Chandler, 1977). Today, the specific technologies driving growth are, of course, quite different than they were a century ago.

*Gary P. Pisano, Harry E. Figgie, Jr. Professor of Business Administration, Harvard Business School, Morgan Hall 417, Boston, MA 02163, USA. e-mail: gpisano@hbs.edu

But the fundamental lesson—that these technologies may require new organizational forms—is as relevant today now as it was then.

This is an essay about organizational innovation and experimentation in the business of science. Science has long been, to varying degrees, connected to innovation and thus to business enterprise. The chemical industry of the late 19th and early 20th century, and the pharmaceutical industry of the post-war period, grew directly out of advances in science. The science–business linkage is not new. During much of the 20th century, companies like DuPont, GE, Westinghouse, IBM, Kodak, Xerox (PARC), and of course AT&T (Bell Laboratories) pursued serious science inside their corporate laboratories. However, the nature of the connection between science and business in recent decades has begun to change in important ways. On the one hand, we have witnessed the decline of the corporate industrial laboratory. Many were shuttered or spun off (e.g. Bell Labs, Xerox-PARC) and others were scaled back, or redirected to more traditional "development" roles. At the same time, we have seen the emergence of a whole new class of entrepreneurial firms in sectors like biotech, nanotech, and more recently in energy that are deeply immersed in science. These firms often face decades or more of highly risky and highly uncertain research before they even hope to earn a profit. They are squarely in the business of science. And they are not alone in the pursuit of profit from science. Universities have become aggressive in appropriating monetary returns on their intellectual property through licensing and spin-offs. They have become central figures not just in the intellectual pursuit of science, but also in the business of science.

This essay is organized as follows. Section 2 provides a brief summary of three core Chandlerian propositions. These three are chosen not for their completeness, but for their relevance to transformation of science into a business. I have intentionally kept that section quite short, as this Special Issue of *Industrial and Corporate Change* contains other articles with more complete and deeper reviews of Chandler's contributions. Section 3 examines the changing nature of the science–business interface and describes the emergence of a science-based business as a novel organizational form. Section 4—Can Science Be a Business?—examines the institutional and organizational challenges created by this convergence. I argue that science-based businesses face unique challenges as they straddle two worlds with very different time horizons, risks, expectations, and norms. Whereas once these challenges were managed inside the boundaries of corporate R&D labs—under the auspices of Chandler's visible hand—today the invisible hand of markets increasingly governs them. An assessment of this form of governance against the requirements of science-based businesses suggests a gap and a need for organizational innovation. The essay concludes with a discussion of what Chandler can teach us about science-based business, and the organizational and institutional implications of science-based business.

2. Chandler's core propositions

Through his studies of the rise of the modern corporation and managerial capitalism in the United States, Alfred D. Chandler advanced three core propositions: (i) technological innovation and organizational innovation are interdependent; (ii) new forms of business organization and institutional arrangements are invented to solve specific economic problems; and (iii) organizational and institutional innovation is an evolutionary process—nothing guarantees "we get it right" every time. Together, these propositions constitute what might be called a "Chandlerian perspective" on the structure and organization of economic activity.

2.1 The interdependence of technological and organizational innovation

For decades, scholars have tried to understand the forces that influence the rate and direction of inventing activity.[1] A subset of the innovation community, starting with the work of Nelson and Winter (1982), has long recognized that the "right" institutional arrangements play a critical role in facilitating technical advance and the diffusion of innovations. This perspective clearly has its roots in Chandler's historical studies. Technical advances in steam power, steel making, mechanical engineering, and the like may have made railroads and mass production *technically* feasible, but it was a host of novel organizational and institutional arrangements—administrative hierarchies, professional managers (and business schools to train those manager), formalized capital budgeting systems, accounting and control systems, corporate governance structures that separated ownership and management—that made them economically feasible. Railroads were, in Chandler's words, "the first modern business enterprise":

> No other business enterprise up to that time had had to govern a large number of men and office scattered over wide geographical areas. Management of such enterprises had to have many salaried managers and had to be organized into functional departments and had to have a continuing flow of internal information if it was to operate at all. (Chandler, 1977: 120).

A similar pattern repeated itself in other capital-intensive businesses. Advances in the application of mechanical and electrical power to production (and later chemicals) made mass production technical feasible, but again, without access to capital (made possible by the development of more sophisticated capital markets) and creation of administrative structures to coordinate the diverse activities of these large-scale enterprises, mass production would not have been economically possible. After reading Chandler, it is hard to think about technological innovation as anything but tightly intertwined with organizational and institutional innovation.

[1]See e.g. National Bureau of Economic Research (1962) *The Rate and Direction of Inventive Activity.*

2.2 Organizational and institutional innovation as the product of human invention

Today, it is easy to take for granted such things as separation of ownership from management, hierarchical organizations, multibusiness corporations, capital markets, accounting and control systems, and other scaffolding of modern economies, as if they were somehow "natural." Chandler teaches us that there is nothing natural about them. They were inventions. Indeed, virtually every aspect of the business world around us—every organizational form, every management technique, every formal and informal institutional arrangement, every principle of management, and every management function—is the product of human invention. Chandler also helps us understand that often—but not always—these inventions were made in response to very specific economic problems. As noted above, mass production required large infusions of capital. The traditional owner–manager company, institutionally, was not up to that economic task. To raise the requisite amounts of capital required capital markets, and a separation of owners (investors) from managers. The rise of professional management as an occupation was an invention to deal with the need to run these complex enterprises. Business schools were invented to supply such professionals. Other elements of the US system of higher education, particularly engineering focused schools like MIT, also played a critical role in supplying managerial talent for complex enterprises.

2.3 Organizational and institutional innovation as an evolutionary process

The first two points above provide a false impression that economic need and organizational/institutional innovation mesh tightly. But Chandler teaches us that such a strict functionalist interpretation is flawed. Economic needs arise, but the response of organizations is slow, uneven, and not always perfect. The rise of the modern corporation itself was a constellation of innovations that spanned multiple decades, if not much of the 20th century. Norms about the roles and responsibilities of management, particularly their fiduciary duty to shareholders, probably evolved more in the last two decades of the 20th century than they did during the first eight. Not all organizations responded immediately. Even within the US national context, some responded with a lag and others not at all. The differences get even larger as one moves across international contexts.

The notion that novel institutions and organizations always arise to enhance economic efficiency does not stand the test of historical analysis. Business trusts were also an organizational innovation of the late 19th century. It would be hard to argue that these were in any way motivated by a desire to increase economic efficiency, or that they had had any positive impact on efficiency. It took another institutional innovation—antitrust law—to rectify the problem.

Chandler's analysis covered a period of great economic, technological, and social change in American industry. The propositions above help to explain the way institutions—particularly business organizations and markets—evolved to adapt to the challenges created by these changes. In short, a Chandlerian explanation for US economic success in the 20th century would place a great deal of weight on the country's superior ability to invent, adopt and adapt innovative organizational structures and practices. Looking at the 21st century through a Chandlerian lens puts organizational and institutional innovation sharply into focus.

There are many potential transformative forces shaping business organization in the 21st century. The one I would like to focus on in the remainder of this essay concerns science, and in particular, the way in which business participates in and shapes science. Recent decades have witnessed intensive organizational experimentation in the way science is generated, diffused, and commercialized. Advances in the sciences of life, energy, and materials offer huge promise both to drive economic growth and improve welfare. Yet, to believe that promise will be realized without organizational and institutional innovation would be to ignore the lessons of Chandler.

3. Science-based business as a novel organizational form

It is often believed that science and business occupy separate worlds, philosophically and physically. Like the separation between church and state, though, the boundary between science and business has always been more approximate than precise. On the one hand, science and business are associated with distinct institutions and norms. Throughout much of the 20th century, it would be reasonably accurate to state that science lived *largely* in the province of the university, and applications of science ("development") lived largely in business enterprises. The notion of such a "division of labor" can be traced back as far as ancient Greece, which emphasized a sharp distinction between "philosophical pursuits" and "practical arts" (Stokes, 1997). Much of the invention of the British Industrial Revolution was carried out by what Ashby called the "hard heads and clever fingers" of the self-taught "craftsman-inventor, the mill owners, the iron-master."[2] Starting in the 19th century, as universities, first in Europe and later in the United States, provided institutional homes for basic scientific research, this separation became more deeply entrenched. As Stokes (1997: 42) writes: "As pure science was being provided with an institutional home in the universities, the sense of separation of pure from applied was being heightened by the institutionalization of applied science in industry."

This separation was not only physical and institutional, but as Merton points out cultural as well (Merton, 1973). Science is a world focused on "first principles" and methods; in contrast, business worries about commercially feasible products and processes. Science is inhabited by academics; the manager, the industrial

[2]Cited in Stokes (1997: 35) and Ashby (1958: 50).

scientists, and the engineer dominate business. Both science and business are intensely competitive worlds but their markets and currency are distinct. In science, score is kept by peer review and grant givers, and measured ultimately by reputation; in business, score is kept by capital markets and measured by profitability. Publication is synonymous with science, secrecy synonymous with business.

On the other hand, it would be hard to deny that by the 20th century, these worlds were converging. By the first decades of the 20th century, a number of US universities such as MIT, Purdue, Cornell, and the land-grant colleges saw applied research as just as important to their missions as fundamental scientific research (Mowery *et al.*, 2004). The growth of departments of applied science and engineering (incorporating fields like electronics and computer science) in US research universities served as a bridge between the worlds of fundamental research and practice. In the late 19th and early 20th centuries, chemical companies began to create in-house capabilities for relatively fundamental research in chemistry. Throughout much of the 20th century, a number of large US enterprises, including DuPont, Corning, Dow, General Electric, Westinghouse, Xerox, Kodak, IBM, and of course AT&T, created corporate research laboratories capable of pursuing leading edge science (Hounshell and Smith, 1989; Shapin, 2008). A small number of Nobel Prize winners in Chemistry and in Physics even came from industrial laboratories. Many of these laboratories, like their academic counterparts, provided their scientists relatively wide latitude to pursue research projects and even publish their findings in academic journals. Even the supposed clean distinction between the norms of science in academic setting and the prevalent norms in industrial settings has recently been called into question (Shapin, 2008).

However, the fact that the science-business boundary has long been blurry should not obscure three salient features of the business of science in the 20th century. First, to the extent private companies engaged in basic research, this was largely the province of large-scale industrial enterprises like those named above. Mowery (1990) has argued that antitrust constraints played a critical role in motivating the largest firms—like DuPont, Kodak, IBM, and others—to invest in research in order to find avenues for growth other than mergers within their core businesses. Indeed, many of the storied corporate research laboratories—DuPont, Kodak, IBM, AT&T, Xerox—are also associated with landmark antitrust cases. Second, new entrepreneurial firms, while playing a critical role in the commercialization of innovation, particularly in the electronics industry, were not themselves engaging in significant scientific research. Finally, while academic institutions in the United States were certainly involved in "applied" research, and were influenced by the needs of industry and local economies, they were not major players in the "business" of science. These three elements of the innovation system began to change in the later decades of the 20th century with the emergence of biotechnology.

3.1 *Biotechnology and the business of science.*

In the latter decades of the 20th century, fundamental elements of the US innovation system, and in particular, the way science and business connected, began to change. To some extent, these changes are tightly connected to the emergence of bioscience and biotechnology, but they may portend deeper and more durable shifts that influence more generally how science moves from the lab to the market.

The first of these changes was the demise of the central corporate research laboratory. It is difficult to put an exact date on this process, but certainly, 1984, the end of the landmark AT&T antitrust case, would be high on the list. Unshackled from the 1956 antitrust consent decree that prevented AT&T from entering the telecommunications equipment business, the 1984 settlement also exposed the corporation to competitive forces for the first time. Over time, it became clear that fundamental research was a luxury AT&T could not afford. A similar story played out in many other laboratories. Increasingly competitive markets, combined with a shift in corporate governance principles that placed greater emphasis on maximizing short-term shareholder returns (Lazonick and O'Sullivan (2000)), led to the shuttering or curtailing of corporate research laboratories, including those at Xerox, Kodak, IBM, and GE. And even DuPont, by the 1980s, was asking its research laboratories to focus more on the commercial needs of the existing businesses (Hounshell and Smith, 1989).

The second trend was the increasingly active (and some might say aggressive) role played by universities in seeking to capture financial returns on intellectual property. This new stance is often attributed to the passage of the Bayh-Dole Act in 1984 but as Mowery *et al.* (2004) demonstrate, the growth of patenting and licensing began its upsurge in the 1970s. Regardless of the underlying cause, there is little doubt that universities have become much more active participants in the business of science through patenting, licensing, and, in some cases, direct investors in spin-offs. While there are historical antecedents of such activities, the intensity of these efforts expanded dramatically in the latter decades of the 20th century (Shane, 2002, Sampat and Nelson, 2002, Thursby and Thursby, 2002, Mowery *et al.*, 2004). As Shapin (2008) notes: "[F]from the beginning of the century to about the 1960s and 1970s, the generality of academic scientists and administrators remained unfamiliar with the academic production and management of commercializable knowledge (p. 211)."

The final change is the emergence of specialized "science-based businesses" largely in life science, but also in nanotechnology and more recently in the energy sector. In earlier work (Pisano, 2006), I defined science-based business as entities that both participate in the creation and advancement of science and attempt to capture financial returns from this participation. They are not simply "users" of science, but contributors to it as well. The science-based businesses of biotech engaged directly in research that would normally have been considered "natural" for a university but not for a for-profit firm, and certainly not for start-up firm. Throughout the history of biotech, starting with recombinant DNA and monoclonal antibodies, but later with genomics, stem cells, systems biology, RNA interference, and others, entrepreneurial firms (often by academic scientists) engage in "raw" science (Pisano, 2006).

Consider the history of the biotech pioneer Genentech. The firm was founded in 1976 by Robert Swanson, a venture capitalist, and Herbert Boyer, a Nobel laureate biochemist and co-inventor of a foundational technique for genetic engineering. The founding of Genentech is significant, not only because it launched the biotechnology industry, but also because it put basic science into the organizational envelope of a for profit firm. Genentech's first research project, supported with funds raised from venture capitalists, investigated whether a human protein could be made in a bacterial cell. At the time, this question was a central theoretical concern in the field of biology.

Note, unlike the industrial labs of decades earlier, which existed within the boundaries of large enterprises with *significant revenue streams from existing products*, Genentech was, in its earliest days, a pure research organization. When it went public in 1980, it had no product revenues. It was still 2 years away from the launch of its first product (recombinant human insulin, developed and marketed by a corporate partner Eli Lilly) and 5 years from the launch of its first wholly owned product. Genentech demonstrated the feasibility of being a science-based business, and it created a template for literally thousands of entrepreneurial firms and bioscience firms founded over the subsequent 35 years (Pisano, 2006).

It needs to be emphasized that science-based businesses are different than traditional "high technology" start-ups that the United States has excelled at spawning for decades. For many decades during the 20th century, the United States was particularly adept at producing entrepreneurial firms in technology sectors like electronics, computers, and software. But the science-based businesses of biotechnology are qualitatively different from the traditional US "high tech" start-up. In the electronics industry and the software industry, start-up companies were by and large engaged in a process of application and development of existing science. Pioneers in electronics like Fairchild and Texas Instruments certainly faced significant technical challenges. But, unlike biotech companies or firms in a field like nanotechnology, the electronics pioneers were working from a reasonably well-developed scientific base. This allowed them to launch commercial products relatively quickly. Fairchild Semiconductor, the pioneering semiconductor firm, had its first products on the market in about 2 years from its founding. Intel, founded in 1968, had a product on the market by 1970. In software, the lag times are even shorter. Engaging in science means that science-based businesses confront an unusually higher risk profile and longer-term time horizon than in other contexts, including "high technology."[3]

[3]One might argue that the longer time horizons in biotech are largely due to the need for human clinical testing. This is only partly true. Certainly, clinical trials add 5–10 years to the development process, but it is should be noted that biotech firms often spend many years simply getting their first

Many of the science-based businesses of biotech were founded by academic scientists looking for a vehicle to further develop and commercialize the fruits of their research (Zucker and Darby, 2006). Shapin (2008) notes that while “scientific entrepreneurs” could be found earlier in the century, it was not until the 1970s that they began to occupy a central place in the entrepreneurial landscape. To a greater degree than before, these scientific entrepreneurs often keep one foot in the world of academia and another in the world of business.

The science-based businesses of biotech are a novel organizational form. Unlike the corporate labs of decades past, they face the winds of market forces without the buffer of rich revenue streams and dominant (and in the case of AT&T monopolistic) market positions. And, unlike the start-ups of electronics, computer, and other classic “high tech” industries, they face prolonged periods of risky investment in research. As we discuss below, this organizational form faces distinct economic challenges, and an analysis of these problems suggests avenues for organizational innovation.

4. Can science be a business?[4]

Science-based businesses confront three fundamental challenges: (i) the need to encourage and reward profound risk-taking over long time horizons (“the risk management problem”), (ii) the need to integrate knowledge across highly diverse disciplinary bodies (“the integration problem”), and (iii) the need for cumulative learning (“the learning problem”). While each of these challenges—risk, integration, and learning—is present in varying degrees in most business settings, in science based businesses all three appear in far greater force and often simultaneously. In each science-based business, it is not a question of whether to worry about risk, integration, *or* learning; one must manage all three at the same time.

4.1 “The risk problem”

Basic technological feasibility is not an issue confronting R&D in most industries. When a car designer sets out to develop a car, they may be confronted with a host of complex engineering problems that will influence the aesthetics, performance, comfort, and reliability of the vehicle. But they can be virtually certain that at the end of the process, the car will work. Even in high tech sectors like semiconductors, high-performance computers, telecommunications, and aircraft, scientific feasibility

product candidate ready to begin clinical trials. Moreover, given immaturity of the science, the odds are against. The vast majority of clinical drug candidates fails. The technical uncertainty in biotech is orders of magnitude greater than in electronics.

[4]Sections of this part of the essay are drawn from the author’s previously published “Can Science Be a Business?,” *Harvard Business Review*, October 2006.

is not in question during a project. Projects are built upon a foundation of existing and well-established science.

This is not the case in a science-based business like biotechnology. Whether a drug emerging from biotech will be safe and effective can only be truly determined through years (sometimes a decade or more) of clinical trials. Critics often complain that the process is slow because of regulation or decry the inefficiency of the "trial-and-error" method. In fact, the process is slow and iterative because the scientific foundations for predicting how a given drug will really work inside the human body are—despite amazing progress in the past couple of decades—still relatively primitive.

By definition, science is all about predictive power. A mature science is one where the principles, cause-effect theories, and supporting empirical evidence have accumulated to such an extent that predictions can be made. The science of aerodynamics, for instance, has matured to such an extent that companies like Boeing embody airframe designs in computer models and use computer-aided simulation to accurately predict the flight performance and characteristics of airplane designs. Predictive models reduce risk. Boeing faces considerable financial and market risk in developing a new generation airframe (a $10 billion investment). But, they do not worry, like the Wright Brothers did, that at the end of the process the plane will not fly. In less mature sciences, by definition, predictive power is lacking. Knowledge of the underlying cause–effect relationships may be lacking or only dimly understood. In these contexts, R&D is necessarily iterative.

An important attribute of science-based businesses is that as a result of the iterative nature of R&D, time horizons to resolve fundamental uncertainty can be quite long. Thus, not only might the financial costs of exploration be high, but critical technical uncertainties may not be easily or quickly resolvable early in the development process. And, even if an organization can resolve those uncertainties through research, there is no guarantee the resulting intellectual property will be appropriable. "Deeper understanding" may be critical to further development, but it is generally not patentable.

4.2 "The integration problem"

In recent years, empirical studies have confirmed what Schumpeter (1943) suspected more than 50 years ago. Breakthrough innovation is generally the result of recombination and integration of existing bodies of knowledge (Fleming, 2001). It should not be surprising then that science-based businesses emerge at the intersection of multiple bodies of science. Again, biotechnology and nanotechnology are illustrative. Each is a "new body" of science that results from the integration of a constellation of underlying disciplines such as chemistry, biology, and physics. "Biotechnology" is a catch-all term today that incorporates an enormous underlying mosaic including molecular biology, cell biology, genetics, bio-informatics, computational chemistry, protein chemistry, combinatorial chemistry, and many areas of basic medicine. As a result, one of the biggest challenges of research in these emerging areas is integrating diverse scientific disciplines.

Again, the challenge of the integration is not unique to science, but its character may be quite different given the underlying immaturity of the knowledge base. In areas where the underlying science is more mature, knowledge is often modular. That is, with deeper understanding comes knowledge about fundamental "building blocks" and how those interact. It is thus possible in areas like electronics equipment, automobiles, software, and other mature systems to break R&D problems down into module components. Modularity is important because it allows for a division of labor. In less mature bodies of knowledge, the puzzle is more complex. There may be a sense of different "pieces" but their boundaries may not be clearly defined and how one thing affects the other may not be well understood at all.

Thus, the "integration problem" in science-based contexts is quite different than integration in other more mature high-technology contexts. In science-based contexts, the problem can often not be modularized. Indeed, the very challenge for researchers may be to discover the relevant "modules". Before those are discovered or characterized, it is simply impossible to break up the problem into its subcomponents and attack each separately. As discussed later, this has profound implications for how we think about the organization of R&D.

4.3 "The learning problem"

Combining the first two challenges above leads almost inevitably to the third challenge: learning. Science-based businesses are at the frontier of knowledge. Technical failure is the norm, not the exception. What is known pales in comparison to what remains to be discovered. New hypotheses and new findings must be constantly evaluated, and decisions about what to do next must be made in the fog of limited knowledge. Knowing the right answer is far less important than knowing the right experiment to run.

When failure is more common than success, the ability to learn from failure is critical to making progress. Learning can occur at multiple levels in a system or an industry. A scientist who has spent decades doing research on a particular topic will have accumulated quite a lot of knowledge about their specialty; the lab in which the scientist worked will also have presumably learned some things from this research. This learning will be not only the aggregate of what individuals know, but also the insights shared by the community. Some of this knowledge will be formalized in organizational procedures and methods, but much of it may be tacit.

Immaturity in the knowledge base means there is a strong art to decision-making. Judgment and intuition must suffice where "hard" data and good predictive models are lacking. Again, we can take an example from drug research. Very often, what individual scientists know about the underlying biology of a disease cannot be reduced to precise rules ("if X, then Y"). Data from experiments are subject to different interpretations. What constitutes a strong signal for one researcher may give another pause.

As a result, sharing experiences over an extended period of time matters enormously in such contexts, and the breadth of the sharing is important. For the science to advance, each of the disciplines with expertise needed to solve a problem must be able to leverage their collective wisdom.

4.4 Design specifications of the science-based business

We can think of the above three challenges—risk, integration, and learning—as defining the fundamental "design specifications" of the science-based business. Hypothetically, if we could "design" a science-based business, what problems would we design it to solve? The answer from the above discussion is that we would design science-based business to be good at managing and rewarding long-term risky investments, integrating across bodies of knowledge, and learning cumulatively over time.

It is interesting to test the traditional corporate laboratory again with these requirements. By internalizing the research function, the corporate laboratory dealt with the problem of risk and long-term investment through the internal capital market. As long as the parent corporations of these labs had dominant market positions, excess cash flows, and shareholders focused on the long-term, they could use the internal capital market to fund long-term research. As mentioned earlier, most of the prominent corporate labs lived inside companies with dominant market positions. They also thrived at a time (pre-1980s) when the dominant principles of corporate governance in the United States put greater emphasis on retention of earnings for long-term investment over short-term shareholder returns (Lazonick and O'Sullivan, 2000).

Likewise, the internal governance structure also facilitated integration of different scientific and technical disciplines. For instance, in Hounshell's and Smith's detailed history of DuPont's research laboratories, there is scarcely a mention of DuPont's interaction with outside partners or collaborators. There is, though, quite a bit of evidence of integration occurring across disciplines (e.g. chemistry and engineering). Similarly, the internal governance structure served as a mechanism to capture knowledge over time.

Yet history has also made clear that the corporate lab was far from an ideal structure. Insulation from capital market pressures cut both ways. The corporate hierarchy may have shielded industrial scientists from the short-term financial pressures of the capital markets, but it also prevented them from reaping entrepreneurial rents. A heavily internally focused research program and the lack of external collaborators also meant that companies forfeited opportunities to tap skills, capabilities, and technologies of outsiders. The relationship between the corporate research lab and the business units was also a source of tension in many companies. At DuPont in the 1960s, attempts to use research to drive diversification and growth, for instance, were thwarted by the business units' focus on growing existing businesses (Hounshell and Smith, 1989,). At Xerox, many of PARC labs most storied inventions were ultimately commercialized by spin-offs because they did not fit into the company's existing business models (Chesbrough and Rosenbloom, 2002).

The demise of the corporate lab by no means implies that the science-based business model as manifest in biotechnology or other sectors is ideal. As documented in my previous work (Pisano, 2006), science-based businesses have been anything but an economic success in biotechnology. This organizational form is not well suited to meet the three-part challenges of managing risk over long terms, integration, and learning.

Let us begin with the challenges of funding the science based enterprise. There are generally three source of funding available for a company that wants to undertake risky R&D: venture capital/private equity, public equity, or monetization of intellectual property. Each of these is widely used in today's economy, but each presents some dilemmas when applied to science-based R&D.

Venture capital has been an extremely important funding mechanism for technology businesses over the last half century, and there can be little doubt that venture capital has contributed enormously to the innovative capacity of the US economy. In many ways, venture capital is the perfect funding mechanism for a young R&D intensive start-up. Venture capitalists have expertise that the typical investor lacks. In addition, venture capital is not just a source of funding, but also a governance structure. Venture capitalists typically sit on boards. They can monitor their investments closely and exercise reasonably close oversight and control. This is critical for an R&D venture because the high level of uncertainty needs an adaptive approach to governance. In addition, exercising proper oversight requires a deep understanding of the working of the company, its projects, and its management. This kind of information is simply not available to the typical hands-off investor.

There is only one problem with venture capital. Its time horizon and funding model are appropriate for businesses that can reach a suitable liquidity event in about 3 years. And, given the riskiness of venture capital portfolio, venture capitalists want to be able to spread their portfolio across a broad patch of companies. This means limiting investments in any one company (e.g. typically no more than $20 million). The problem, of course, is that in some science based businesses like biotechnology, it takes a decade or more of R&D and more than a billion dollars of investment to generate a product. Venture capital was never designed to take a company ten years into its mission and to invest anything close to a billion dollars.

This leaves public equity to "solve" the problem. As the experience of biotechnology has shown, public equity investors have been eager (at least until recently) to take over where venture capitalists leave off. While public equity can certainly raise the sums required, as a governance structure it was never designed to deal with companies whose assets are largely composed of R&D projects. Such companies cannot be valued on the basis of earnings. Their value hinges almost exclusively on on-going R&D projects. But trying to value R&D projects for a public equity investor is next to impossible. Information is simply inadequate and disclosure rules leave much room for interpretation. And, even when information is disclosed, it can be hard to know exactly what that implies. For instance, if a biotechnology firm announces that it is about to start "Phase II" trials of a drug, this is often taken as positive news. However, how much is really known about the drug (from previous studies) and how confident the company's scientists are in the drug's eventual prospects is not something to which investors are privy. Similar issues arise for investors trying to interpret progress in other scientifically complex arenas. Firms in science-based businesses with high cash burn rates may feel pressured to move projects along to demonstrate "progress" needed to raise additional capital. But whether such projects merit further investments is difficult, if not impossible, for an investor to ascertain.[5]

An alternative or complementary strategy for a firm to raise capital for its R&D is to "monetize" its intellectual property. That is, rather than trying to develop a whole product and earning revenues on product sales, the company essentially licenses out the project to another firm. Such licensing has become a huge part of the R&D world in most technology-intensive industries. There are literally thousands of R&D agreements and licensing deals that occur every year. One of the chief benefits of intellectual property monetization is that it enables firms to manage risks. It also enables firms with complementary capabilities to access know-how.

Monetization of intellectual property is not a new phenomenon. Firms have licensed intellectual property for more than a century. However, the extent of this IP monetization appears to have grown dramatically in the last few decades. Since science-based businesses rest on intellectual capital, it stands to reason that markets for know-how will play an ever more important role in the future. However, we must also understand that monetization of IP has limits as a device for creating the required integration.

Market mechanisms work best when the relevant "modules" of knowledge are clearly defined. Thus, modularity facilitates collaboration (Teece, 1982). This is one reason Open Source projects like Linux have been so successful. The modular architecture of Linux enables thousands of software developers from around the world to make contributions without ever having to talk to each other directly or to meet face to face. The IP monetization approach is often predicated on an assumption that the IP in question is a discrete module or asset that can be bought and sold. However, as mentioned earlier, in science-based contexts, the immaturity of the underlying

[5]For evidence on this point, see Guedj and Scharfstein (2004).

knowledge base makes it less likely for modularity to exist. This suggests that achieving the required integration through licensing and the market-for-knowhow will fall short in science-based contexts.

Science-based businesses in biotech and elsewhere have "borrowed" many elements of organizational technology (such as venture capital financing, use of the public equity markets for liquidity, monetization of intellectual property) that have been used, often successfully, in other technology contexts such as electronics and software. However, as argued above, science-based sectors create novel organizational challenges around the simultaneous need to manage risk, integrate cross knowledge bases, and leverage cumulative learning. Addressing these challenges calls for new "organizational technology."

5. Applying the lessons of Chandler

The fundamental lesson from Chandler is that while technological progress creates *potential* for economic growth, that potential can only be realized with complementary innovation in organizations, institutions, and management. This lesson has clear implications for science-based sectors of the economy. Progress in the science bases of medicine, agriculture, advanced materials, and energy has enormous potential in coming decades. Yet, this potential will go unrealized without the design of appropriate organizational, institutional, and managerial models. One purpose of this essay was to show that, using the case of biotech as a reference point, we have not yet found an appropriate model for science-based business. This conclusion must be drawn with the significant caveat that not all science-based sectors are the same, and the lessons from biotech may not apply more broadly.

Advancing science creates three basic *economic* problems: managing risk, integration, and learning. Historical experience both before and after the emergence of biotech shows the limits of both ends of the organizational continuum: the visible hand of hierarchies and the invisible hand of markets. Hybrid organizational forms that mix elements of markets and hierarchies would therefore seem to be an attractive avenue for innovation. Interestingly, until the past year, Genentech, arguably the most successful biotech firm in terms of innovative output, was an archetype of this type of hybrid. While often described as a "biotech" firm, it was in fact majority owned (ranging from 55 to 85%) by the Swiss multinational drug company Roche, but operated independently. This arrangement mixed both elements of the market (Genentech shares traded publicly, the Genentech and Roche licensing was done at arm's length) and hierarchy (Roche owned a majority of the shares and had strong Board representation). In 2009, this hybrid arrangement reverted to a more traditional structure when Roche acquired the remaining shares of Genentech it did not own, and Genentech became a wholly owned subsidiary of the corporation.

Organizational networks offer another avenue for innovation. Chandler argued that the firm, not the transaction, was the most important unit of analysis (Chandler, 1992) for understanding the boundaries of organizations and structures. Alternatively, it could be argued that in contexts that mix markets and hierarchies, the *network* of organizations becomes the most interesting unit of analysis (see e.g. Miles and Snow, 1986; Stuart, 1998). Such network organizations are very different from the kinds of "strategic alliances" that have been much discussed in both the academic and popular press over the past two decades. In practice, most "alliances" are nothing more than contractual based relationships, often characterized by mistrust and adversarial bargaining. Network organizations redefine traditional corporate governance. Take for instance the notion that management should maximize value for "its" shareholders. With traditional enterprise boundaries, it is relatively easy to understand whose value it is that should be maximized. Once we move to organizations that are connected in durable networks, this notion becomes much more complicated. The value of the network and the value of individual "firms" in that network become harder to disentangle.

The complexity only grows once we also accept the very real possibility that some of the organizations embedded in these networks may not be for profit firms at all but university laboratories, not-for-profit foundations that fund research at private enterprises, and even potentially government laboratories. While modern capitalist economies have always exhibited the ability to utilize a mixture of institutional forms, in science-based economies the forms themselves begin to blur together. This blurring challenges basic notion of "corporate governance" and the underlying values that guide decision-making.

In an essay in honor of Alfred Chandler, an author would be remiss not to mention "management technology" as a critical component of innovation. Chandler documented the emergence of the professional manager and the innovations in managerial techniques needed to run the organizations he studied. This raises the question of whether current "management technology' is suited to the needs of science-based businesses. Indeed, the very notion of "professional manager," while seemingly quaint, indeed characterizes much of the division of labor between scientists and manager today. Consider that today, scientists receive no formal training in management and MBAs receive no training in science. This is a striking gap. The professions of management and the professions of science are still largely separate.

Like railroads and large-scale manufacturing enterprises on 100 years ago, science-based businesses will be a potent source of economic growth in the 21st century. And now, as then, these new businesses demand new organizational forms and new institutional arrangements. In short, we are once again confronted by a serious need to invent new organizational forms and new institutional arrangements to deal with a new set of economic problems. When it comes to the topic of innovation in business organization, there is no better teacher than Alfred Chandler.

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