Paper to be presented at the DRUID 2011

on

INNOVATION, STRATEGY, and STRUCTURE -
Organizations, Institutions, Systems and Regions
at
Copenhagen Business School, Denmark, June 15-17, 2011

The American System for Creating High Tech Industries: the Historic Place of Greater Boston

Michael Hepburn Best

Michael_Best@uml.edu

Abstract

The developmental process of growing new, global-leading high tech sectors has been a largely unrecognized feature of Greater Boston?s economy in the postwar era. The engine of growth is an open-system business model: the proliferation of mid-size, entrepreneurial firms which collectively generate an evolutionary process of increasing technological differentiation. But without national government funding of public science via research-intensive universities the region would not have established a unique capability to drive industrial transitions.

This paper traces the historical origins and success of the Boston system of high tech to a unique three-branch, triangular system put in place during World War Two to establish an advanced-technology weapons industry. The triangular system was designed, led, and administered by a scientific elite and funded by the federal government. Unintentionally, it laid the institutional foundations for a postwar S&T infrastructure which transformed business organization and regional growth dynamics.

Greater Boston was the first region in which the regional industrial innovation potential of the postwar federal S&T infrastructure was operationalized. The pivotal role of an independent scientific community is illustrated by contrasting Greater Boston with the ?closed-system?, government-client business model of Greater Washington.

Jelcodes:O38,O32

The American System for Creating High Tech Industries: the Historic Place of Greater Boston

Michael H. Best
April 28, 2011

Part One. Introduction and the Argument in Brief

The classic studies of business by Chandler, Schumpeter, and Penrose were all written within the institutional-backdrop of the rise of Big Business.[1] This was the age of the Visible Hand in which giant, managerial enterprises were established to exploit economies of scale and scope; it included the founding of industrial labs to turn science into an organizational resource for new product development and sustained competitive advantage. Small firms, in business history literature and reality, were technologically backward and without access to the product development and innovation opportunities afforded by scientific advance.[2] The intellectual divide was between Chandler's optimistic thesis of *managerial permanence* based on economies of scale and scope on the one hand and Schumpeter's anticipated bureaucratic sclerosis leading to the collapse of capitalism on the other.[3]

Harold Livesay waged a lonely battle for his concept of entrepreneurs as "growth-oriented, innovation practitioners of aggressive management" and his thesis of *entrepreneurial persistence* in firms of all sizes. His historical accounts of the individuals who built and drove what became America's most successful companies are certainly a welcome anti-dote to images of enterprises as organizational charts and anonymous bureaucracies. But his focus, as well, was firmly on the individual firm as an autonomous agent; we find no conceptual space for localized systems of entrepreneurial firms.[4]

Consequently, none foresaw the innovative and emergent properties associated with localized *populations* of entrepreneurial firms, most of which are small and medium-sized. The innovative potential of localized systems of small and medium-size enterprises (SMEs) had been, in effect, written out of the historiographical script.

[1] Schumpeter, Chandler, and Penrose saw the integration of science and industry in the form of the in-house industrial lab as establishing a barrier to entry and with it the passage from history of dynamic small firms. They shared the view that innovation became institutionalized (and science became incorporated) within large business enterprises with the market power to fund R&D laboratories.

[2] SMEs persisted primarily in sectors in which materials were intractable to technological innovations that applied economies of speed and scale that drove down the costs of production.

[3] "once a managerial hierarchy had been formed…the hierarchy itself became a source of permanence, power, and continued growth". "Men came and went. The institution and its offices remained" Chandler (1977: 8).

[4] Ironically, the concept of the Visible Hand reinforced the neoclassical assumption of a firm or market dichotomy and, with it, the image of the atomistic firm akin to the economic man rather than evolving systems of capability-differentiated enterprises.

History took a different course. The post World War Two era ushered in an unexpected period of resurgence of localized systems of high-tech SMEs.[5] Greater Boston and Silicon Valley were the earliest and most notable. The instigators of growth, not for the first time in American history, were localized populations of hundreds and eventually thousands of specialized entrepreneurial firms, most small and medium-sized.[6] These regional business systems do not exhibit the historical trend to ever increasing industrial concentration and the corresponding barriers to entry to SME's. [7]

The Greater Boston region's unique characteristic and competitive advantage became, once again as in age of American System of Manufacturers, the capability to create and grow a diverse range of new sectors.[8] The American System of Manufactures and the Boston System of High Tech are both variations of an open-system business model. But, as will become clear, inter-firm relations, and extra-firm infrastructures are different in important ways.

The open-system business model has not meant that industrial R&D has declined. The Massachusetts private as well as the combined private plus public expenditure on R&D per capita surpasses that of similar sized countries like Finland and Denmark, which along with Sweden have the highest R&D intensities in the world.

The challenge is not to explain the historic persistence of *individual* cases of entrepreneurial firms. Most regions have at least some such firms. The challenge is to explain the 'deep structure', in this case the business system and extra-firm institutions which foster the ongoing proliferation of entrepreneurial firms some of which grow to size but which collectively enable a regional adaptability to change and sustained regional growth. While the rise of Big Business in America was a story of infrastructures **within** multi-divisional firms that enabled economies of scale and scope; the open-system business model is characterized by infrastructures **outside** the individual firm.

Nevertheless, the open-system business model cannot, on its own, explain the development of the Boston System of High Tech. Its origins and ongoing dynamics involve the co-evolution of a

---

[5] In fact, the business model that drove American System of Manufactures was no match for the managerial enterprise that created a series of internal infrastructures and which became the basis for the industries of the second industrial revolution. These sectors did not grow and consolidate in Massachusetts.

[6] This is not to deny that a small number of new entry firms grow extremely rapidly to become big companies and sector leaders. Some do. Nevertheless, even in these cases the growth dynamic in recent decades cannot be explained in terms of the establishment of infrastructures or shared services such as R&D labs **within** multi-divisional managerial enterprises.

[7] The paper is the consequence of a longer term research project that involved the construction of a historical database of US high tech companies designed to characterize regional patterns of technological specialization and business/sector growth dynamics. Earlier publications have drawn upon this database to characterize the company growth profiles of emerging sectors. It became evident that the origins and evolution of high-tech sectors requires an account of the interplay of business development with federal government investment in basic research and higher education and the subsequent evolution of the region's distinctive knowledge base and technological capabilities.

[8] In the words of Peter Temin (2000: 116, 120) "The American System of Manufactures, based on the principle of interchangeable parts, made it possible for the Americans to produce light manufacturing in volumes and prices unattainable in England (2000: 116)". He adds: "Arms production and the American System of Manufactures…laid the foundation for American industrial expansion in both the nineteenth and twentieth centuries (2000: 120)". See also Marshall (1890: 257-58). The American System was first systematically applied at the Springfield Armory in Massachusetts in the years preceding 1820 (Rosenberg 1976; Best 1990; Hounshell 1984).

unique combination of an open-system business model at the regional level and of an S&T infrastructure funded at the national level but administered locally.

Most importantly, the Boston System of High Tech and industrial innovation does not involve a two-way relationship between federal funding of S&T and Boston area business enterprises. Instead, it is a triangular system involving three inter-related spheres: Government funding of S&T and technology-driven enterprises mediated institutionally by a university-based, independent scientific community. The core of the triangular system is an overlap of two S&T infrastructures: the S&T infrastructure of the federal government and the extra-firm S&T infrastructure of a regionally-based, open-system business model.

Both the origins and the reinvention of the open-system business system were initiated by government sponsored, weapons industry programs. But the reinvention takes us to World War Two and the revolution in the role of science first in government and then industry. At this point in history a national science and technology infrastructure was designed and put in place with profound effects on business organization in America.

It was during World War Two that a unique '**three branch**' governance structure was put in place to oversee the creation and rapid growth of America's first high tech industry, that of technologically advanced weapons. The extraordinary success of the rapidly created, scientist-led industry in designing, developing, and produced technologically advanced weapons permanently altered the inter-relations of government, science, and business in the economy.

Science was, in effect, unshackled from severe prewar budget constraints and a government-funded but university-administered science and technology infrastructure was institutionalized. The postwar consequences for business and industrial organization were unintentional but profound. The industrial labs of Big Business no longer had an effective monopoly over the commercial application of science; university and government labs opened the doors of scientific research to technical education and to technology-oriented business-development initiatives. Greater Boston system of high tech is not the only variant. But it was the first and was the model for Silicon Valley; Bush has also been called the father of the Greater Washington high tech system which is remarkably different from the first two.

But the story below begins in Washington DC and the wartime creation of an administrative agency with the mission to overcome the nation's weapons technology gap with Germany. The artful integration of inputs from government, science and industry was the prototype for the postwar S&T infrastructure. Vannevar Bush, scientific advisor to President Roosevelt, was the organizational architect and political engineer. In Part 3, I examine the 'first mover' advantage and model of MIT in leveraging the new national S&T infrastructure to foster regional high tech industrial growth. The rapid growth and development of the minicomputer industry in Greater Boston illustrated the power of the national S&T infrastructure to foster the creation of high tech companies. But it was only an intermediary phase in the transition to the open-system business model that came to characterize Silicon Valley and Greater Boston. This is elaborated in Part 4.

In Part 5 we return to the nation's capitol to provide a contrast closed-system business model to that of Greater Boston. Here we find a direct federal subsidization of business approach to the establishment of a high-tech region but without mediation by an independent scientific community. The principle of open-research is as critical to the emergence of the postwar open-system business model as it was to the wartime establishment of advanced technology weapon systems. Implications are drawn for policy and regional growth dynamics in Part 6.

Part Two. World War II and Origins of the Three Branch Model [9]

German leadership in the application of science to the weapons industry created a formidable organizational challenge to the United States as it emerged from two decades of isolationism. A technologically advanced weapon was no ordinary product. It required the integration of elite scientists with highly specialized skills and capabilities from industry and the Germans already had an organizational system in place. The German state drafted scientists into military labs to design and develop weapons for production in government directed or owned industrial enterprises.

In contrast, interwar period America's investment in science research was small and institutionally fragmented. Federal establishments such as the agricultural experiment stations, the Smithsonian Institute, and military laboratories employed a limited number of scientists. The corporation labs were concentrated in a handful of oligopoly industries but like the federal establishments, few conducted basic research. A limited number of universities did conduct basic research but the scale was pitifully small. Industrial enterprises that sponsored research at universities like MIT did not fund basic research and total sponsored research declined not only during the 1930s but during the 1920s as well.[10]

America's industrial leadership was based on the mass production industries of the 'second' industrial revolution and the managerial innovations of Big Business. Add in the budget constraints of the Great Depression and it is no surprise that federal expenditure on R&D was not a popular rallying cry.

The success of the German war machine was the national wakeup call. Leading scientists and engineers had been warning that the German weapon system technological superiority was advancing rapidly and the American military was not aware, equipped, or prepared to address the challenge. European émigré scientists such as Einstein, Szilard, Fermi, and Wigner knew first-hand of advances being made by German scientists in designing an atomic bomb and rocketry. But as émigrés they were distrusted by the military brass and in no position to shape federal policy.

[9] In this section, I draw heavily from G. Pascal Zachary's biography titled *Endless Frontier: Vannevar Bush, Engineer of the American Century* (MIT: 1999).
[10] Receipts for MIT's Technology Plan, designed to build closer industry-university relations for basic research, mission-oriented research and product development research, declined from the first year of $424,090 in 1919-20 to $27,621 in 1926-27 (Etzkowitz 2002: 45). See also Davis and Kevles (1974) and Owens (1990).

President Roosevelt was acutely aware. "Undetectable' German U-boats were sinking ships at a high rate making the Atlantic shipping lanes increasingly precarious.[11] Warnings from émigré scientists warning of the threat were reinforced by ongoing conversations with Winston Churchill as to the precariousness of the British situation and the desperate need to employ scientists in the war effort.[12] British scientists were developing high-tech weapons system prototypes such as radar, the proximity fuse, as well as code-breaking devices. But they lacked the industrial engineering expertise and production capabilities to manufacture to scale.

The story of the embrace of science for strategic military purposes in America leads straight to Vannevar Bush hailed as the 'man who won the war' by *Time* magazine and the 'Engineer of the American Century' by G. Pascal Zachary, his biographer. Although unrecognized as such even by himself, he was also the unwitting architect of America's high-tech regional systems.

A native Bostonian, Bush was uniquely knowledgeable about the university-industry interface. He had been the co-founder of small engineering-led firms one of which became Raytheon. His academic role spanned science and engineering research and administrative leadership. He had been the Dean of Engineering at MIT, was the holder of numerous patents including the invention of a mechanical calculator.

In the interwar years, Bush was an unsuccessful applicant for military funding of radar development. As a leader of the scientific community, he was convinced that neither military leaders nor politicians comprehended the threat of new weapon systems being developed by German scientists. Without political leadership and federal funding, the nation's military power could not match the German capability in technology-advanced weapons.

In 1939, Bush turned down the presidency of MIT to take leadership of the Carnegie Institute in Washington DC. The Carnegie Institute funded scientific research but it was also in Washington DC where potentially it could influence federal funding of R&D to address America's 'technology lag' in weapon systems (*NYTimes*, Zachary: 158). Bush and fellow scientists' concern was that military leaders were committed to existing weapons systems and industrial labs did not have the directive or the scientific expertise to design, develop, and produce weapon systems to match those of the Germans.

Zachary provides an account of how Bush used his position as a leader of the scientific community and his connection with a relative of President Roosevelt's in investment banking to meet with and gain the confidence of the President. Bush saw the President as a means of doing an end-run around the military establishment to put himself in charge of science-based weapon systems research and development. The President was easy to convince.

President Roosevelt signed a 5 page memo written by Bush which established the National Defense Research Committee (NDRC), composed of scientists, with Bush as chairman in 1940. In May 1941, President Roosevelt approved the creation of the Office of Scientific Research and

[11] "In 1941, the Allies lost 875 ships in the Atlantic…[and]…in the first six months of 1942, another 490 ships were sunk off the U.S. eastern seaboard despite the presence of no more than a dozen U-boats" (Zachary 1999: 160).
[12] Albert Einstein's famous letter to Roosevelt warning of the atomic bomb was in 1939 (Zachary 1999: 205).

Development (OSRD) which took over the functions of the NDRC but received direct funding from Congress and gave it a legal foundation. This gave Bush the governmental authority to fund research to design, develop and produce weapons outside the military command structure (Zachary 1999: 129).

Bush's organizational vision was uniquely decentralized. Whereas the German concept was to employ scientists within the military and to make industry subservient to state directives, Bush's concept was to establish a mission-driven agency within the government to administer a three-way partnership amongst the scientific community, industry, and the government subject to the necessary condition that the terms of the partnership respected and leveraged the autonomy and distinctive roles of each.

Bush knew that mobilizing the energy and commitment of scientists was necessary and that it would not work to put European émigré scientists under the command of military officers or government officials. The clash of cultures was too sharp particularly with the émigré scientists strongly held commitment to the ideals of open research and free speech. His organizational solution was to enlist the scientists of the nation's elite universities by funding research at or by scientists and engineers at university-administered laboratories. The OSRD set the terms of reference, funded and evaluated, but did not conduct, research. The basic research carried out at universities would be complemented by the research and engineering departments of enterprises to operationalize the requisite product development and ramp up production capabilities.

The revolutionary character of the government's relations with the scientific community were captured in the words of James Conant, President of Harvard University and a member of the OSRD Committee: "I shall never forget my surprise at hearing about this revolutionary scheme…Scientists were to be mobilized for the defense effort in their own laboratories. A man who we of the committee thought could do a job was going to be asked to be the chief investigator; he would assemble a staff in his own laboratory if possible; he would make progress reports to our committee through a mall organization of part-time advisers and full-time staff" (Conant 1970: 236, quoted in Zachary 1999: 115). See also Etzkowitz (2002: ch. 4).

The war time numbers reflect the massive funding for weapons systems that ushered in the expansion of the new system. Total federal R&D expenditures increased over 15 times (in 1930 dollars) from $83.2 million in 1940 to $1,313.6 million in 1945. The Manhattan project's research budget surpassed that of the Department of Defense.[13] MIT, the largest university recipient, signed seventy-five OSRD contracts for a total of over $116 million (Mowery and Rosenberg 1993: 39-40). In all, OSRD directed 30,000 men and oversaw development of some 200 weapons and instrumentalities of war, including sonar, radar, the proximity fuse, amphibious vehicles, and the Norden bomb sight, all considered critical in winning the war. At one time, two-thirds of all the nation's physicists were working under Bush's direction. In addition, OSRD contributed to many advances of the physical sciences and medicine, including the mass production of penicillin and sulfa drugs.[14]

---

[13] The OSRD controlled the Manhattan Project until 1943 when administration was assumed by the Army.

[14] The history of the extraordinary successes of the OSRD is now part of military folklore. Radar systems developed at the MIT radiation laboratory and mass produced at Raytheon, once deployed, secured the uninterrupted flow of supplies to Britain. The proximity fuse, using vacuum tube technology (another Raytheon capability), were first

When victory was in sight, President Roosevelt asked Bush (probably at Bush's invitation) to write a report on the lessons to be learned from the war mobilization of science for peace time including implications for the economy and economic growth. The result was *Science: the Endless Frontier. A report to the President on a Program for Postwar Scientific Research* (July 1945; Reprinted July 1960, National Science Foundation, Wash. DC). This extraordinary document signaled the new era in the government's approach to science and transition to the postwar inter-organizational research management system.

Federal R&D spending, while following immediately after the war, increased from about 0.5 to nearly 2 percent of GDP between the early 1950s and the early 1960s; federal and non-federal R&D spending as a percent of GDP more than doubled from under 1.5% to nearly 3% over the same period (Mowery and Rosenberg 1993: 40).

These numbers reflect the institutionalization of the inter-related roles of government, the academy, and industry established during the War. They reflect Bush's vision of the separation of funding and administration of research: instead of government employment of scientists, government funded contracts would go mainly to universities, to new federal laboratories administered by leading research universities or to non-profit, privately managed research institutions.

In 1946, the RAND Corporation, was established at Douglas Aircraft in southern California under an Army Airforce contract. It was the nation's first FFRDC (Federally Funded Research and Development Center). Since then more than 700 FFRDCs have been established. These non-for-profit, federally contracted centers could pay salaries outside those of federal employment contracts, they are administered by non-government agencies, and they could be located anywhere in the United States. They cannot be involved in manufacture or production of hardware. For this they need industry partners.

Bush's vision of federally funded, university administered R&D laboratories was turned into a centerpiece of government policy. The nation's first science advisor, Bush served under Roosevelt, Truman, and Eisenhower. He was the first of a series of MIT professors prominent in the formulation of national science and education policy including Jerrold Zacharias, James Killian, Julius Stratton, and Jerome Wiesner (Warsh 1988: 326).

Part Three. America's First High-tech Region: Triangular Relationships

On the eve of World War II MIT was an exceptionally successful science and engineering school noted for an elite education, fundamental research, and close links to technology-oriented, industry-leading enterprises. The latter included Bell Telephone and General Electric. Over a period of five decades it had negotiated, not without considerable internal debate, a model for

deployed to stop air attacks on US ships in the Pacific to great effect. They were then turned to counter V1 rocket attacks on England and supplied to allied ground troops late in the war.

university and industry partnerships consistent with the principle of open scientific research. Vannevar Bush was a champion of the model while dean of engineering at MIT. But it was not an arrangement which resulted in substantial industry funding of basic research. Consequently, external funding for basic research was always in short supply even at MIT. (Etzkowitz 2002; Rosegrant and Lampe 1992).

Nevertheless, two elements of the new postwar business development and regional innovation system were in place, if as yet on a small scale: independent scientists working at the cutting edge of advanced technologies and companies seeking to compete on the basis of leadership in new technologies. The third element was missing: the availability of funding for basic research.

The missing element was supplied as the federal government stepped in as a full-fledged partner with elite universities. In 1940, MIT's Division of Industrial Cooperation administered less than $100,000 worth of research contracts. By September 30 of the next year, MIT's research contracts, mostly from the federal government, had topped $10 million (Rosegrant and Lampe: 1992:72).

The wartime case of federal funding of microwave research illustrated the power of the new mutually symbiotic system to advance the diverse goals of government, industry, and university. The federal funding began when a team of British scientists brought a single small magnetron (the microwave generating tube at the core of the machine) to the United States in 1940. An industry/university partnership in the form of Raytheon and MIT seized the opportunity and went to work.

Raytheon had been founded in 1922 by Laurence Marshall and Vannevar Bush as the American Appliance Company, a maker of machinery, motors and components. While Raytheon's history involved collaboration with MIT from the beginning, the company's growth and region's distinctive microwave technology capability were a consequence of Raytheon's engineering production capability. Britain could not produce enough machines. The reason, however, was not simply a lack of machinists during wartime. Raytheon engineers came up with a "novel way to boost production…by assembling them out of laminated sheets instead of carving them laboriously out of solid blocks" (Rosegrant and Lampe 1992: 84). Instead of the predicted limit of 100 megnetrons per day, Raytheon's engineers' technique was producing 2000 a day. Raytheon's production capability spurred the development of the technology.

In five years a new industry had sprung up around Boston's Route 128 converting Raytheon from a small vacuum tube producer into the region's largest defense contractor. Raytheon's employment increased from 1,400 to 16,000 between 1941 and 1945 (Rosegrant and Lampe 1992: 85). The legacy of leadership in microwave technology is manifest in an array of telecommunication companies in greater Boston today (Best, Paquin, and Xie 2004: Table 1, p. 11).

In the postwar era, FFRDCs became an organizational model for funding R&D at the regional level. FFRDCs were pivotal to the establishment of Greater Boston as America's first high tech regional economy. In the case of Greater Boston, FFRDCs were the agencies that integrated the region with the national S&T infrastructure; one cannot be described without the other. The

FFRDCs were the physical sites in which the three estates interfaced. The power of the postwar variant of the three branch system to develop technologies and complex product systems was first and amply demonstrated in Massachusetts.

The prototype was the MIT-administered Radiation Lab. At its wartime peak, it employed over 4000 scientists and engineers in over 15 acres of floor space in Cambridge. Rosegrant and Lampe write that the Radiation Lab, went on to develop over 150 systems "that applied the versatile microwave technology to a dizzying array of applications" (1992: 84). Lincoln Labs, established in 1951 following the Soviet Union's detonation of an atomic device in 1949, succeeded the Radiation Lab. In 1958, MITRE Corporation, a non-profit corporation was established next to Lincoln Lab at Hanscom Air Force base on Route 128 to focus on systems integration. MITRE, also administered by MIT, grew to employ thousands, mainly engineers and scientists.

New generic technologies developed in Massachusetts in the postwar decades include microwave technologies, the digital computer, guidance systems, and the Internet. The federal government funded basic research for all four under defense related budgets. The first three were developed in FFRDCs linked to MIT. The fourth, packet switches, the key Internet technology, was developed (not invented) at Bolt Beranek and Newman (BB&N, a private research company founded by three MIT professors).

FFRDCs were prohibited from manufacturing activities. For this they needed industrial partners. Industrial partners were presented with a science and technology infrastructure unmatched by any but a handful of corporate labs.

The most famous example is of the building of the world's first reliable digital electronic computer at MIT's Lincoln Labs in 1953, followed by the founding and growth of Digital Equipment Corporation in 1957. At its peak in the early 1980s, DEC employed 124,000 and led in the establishment of the region's minicomputer industry. While an MIT student, Ken Olsen, DEC co-founder, worked at Jay Forrester's Servomechanism Lab, funded by the Office of Naval Research to build a flight simulator for purposes of training pilots. This project morphed into the Air Force's Whirlwind project which needed a 'brain' to build the first real-time, non-computational computer for SAGE (Semiautomatic Ground Environment), America's air defense system.[15]

While computers were dubbed the "brains" of an automated air defense system, at the same time, an air defense system involved the integration of technologies underlying missiles, radar networks, gunfire control, guidance systems, as well as high-speed digital computers (Hughes 1998: 17). No region could match Massachusetts for the rapid development of complex product systems involving such a diverse range of technologies.

[15] The development of SAGE at MITRE was the first successful effort to "apply computers to large-scale problems of real-time control as distinct from calculation and information processing" (Edwards 1996: 16; cited in Hughes 1998: 28). The Whirlwind project designed and developed the Magnetic Core Memory, a breakthrough innovation which became the heart of IBM's System 360. Olsen helped develop the Magnetic Core Memory while at Lincoln Labs before leaving in 1957 to form DEC (Rosegrant and Lampe (1992: 91).

Thus computer development in Massachusetts was but one technology in the development of the region's emerging systems integration capability. In this Hansom Air Force Base on Boston's Route 128 was no ordinary air force base. It is home of the Electronics Systems Center (ESC) the Air Force's site for C^4I management. C^4I is a defense industry acronym that stands for command, control, communications, computers, and intelligence. The ESC's role is concept development and systems integrator. It has managed nearly 200 C^4I systems.[16] It has contributed immeasurably to the region's unique capability and skill base in systems integration.

MITs impact was not limited to the Boston area. It became a widely emulated model for regional 'boosters' in the form of technology-based economic development initiatives anchored by university/industry partnerships. None was more successful than that of Frederick Termin, a student of Vannevar Bush's at MIT and often dubbed the father of Silicon Valley (Leslie and Kargon 1996; Lecuyer 2006).

Rarely have these efforts been successful establishing localized 'industrial districts' with the capability to drive sectoral transitions. All too often they are not based on an understanding of two features of the Boston System of High Tech. One is the role of the federal government in funding R&D via the triangular system described here. A second is the lack of attention to the complementary role of open-systems business models in fostering innovation.

Part Four. Greater Boston's Open-system Business Model

The ongoing process of not only creating but growing high-tech companies over many decades is perhaps Greater Boston's best kept secret. Many other regions have research intensive universities and some have strong records of spin off companies from university laboratories but no region, other than Silicon Valley, has the demonstrated capability to grow numerous startups to mid-size companies. These companies are the growth engines of new sectors, a process for which over an extended period even Silicon Valley does not match the success of Greater Boston.

The success of Greater Boston in these closely-related processes of firm and sector growth has been largely invisible in academic research. Part of the reason was the highly growth and then more rapid collapse of the minicomputer industry. For many the industry was a metaphor for high tech in the region. Annalee Saxenian's classic study contrasting the business systems of Route 128 and Silicon Valley characterized the business model of the dominant firms in the Greater Boston minicomputer industry as autarchic.

In this she was right. Rivals in the minicomputer industry did not cooperate. Communication by employees of one company with those of another was discouraged for fear of loss of intellectual property and staff to rivals. Consequently, innovation in the Boston area computer industry was internalized within a vertically-integrated, closed-system business model and the region lost out to the superior innovation dynamics of a rival open-system business model of Silicon Valley.

[16] The ESC is a systems acquirer and integrator: "In its system acquisition mission, ESC serves as manager; determining the eventual user's operational needs, defining systems to best meet those needs, soliciting proposals from industry, selecting contractors to build the product, monitoring the contractor's progress, and eventually testing the equipment to ensure it meets the user's requirements" (p. 1-3, ESC).

Whereas DEC made or at least designed all of the elements in its computers, Intel specialized on the microprocessor and specified the system architecture, HP on printers, Seagate on disk drives, etc.

The closed-system business model was not limited to the minicomputer industry. Even with the central role of MIT and Harvard in Greater Boston, the early postwar military funded research programs risked pushing the region's business system in the direction of closed research behind the shield of classified research. The region's biggest industrial enterprise, Raytheon, was a prime contractor for the Department of Defense and had hundreds of sub-contractors conducting classified research.

Nevertheless, in contrast to accounts of the decline of Route 128, Massachusetts ranks very high on various indicators of industrial innovation, technological diversity, and economic performance. In studies of high tech regional concentration Greater Boston continues to lead the nation. Route 128 (in this case the Cambridge-Newton-Framingham Metropolitan Division with roughly 1.5 million population) ranks number 1 of 200 metropolitan regions in the US in High-Tech GDP location quotient for 2008 (2.84) and number one in the number of High Tech GDP location quotients over 1 for 2008 with 18 (DeVol, Bedroussian, Klowden, Flor Hynek 2009). Using a range of 17 'new economy' indicators, The Progressive Policy Institute ranks Massachusetts first in the US. The 17 indicators are divided into 5 categories: knowledge jobs, globalization (manufacturing exports plus foreign direct investment), jobs in fast growing companies, diffusion of digital economy, and 'technology innovation capacity.[17] Manufacturing exports from Massachusetts of $67,000 per million dollars of state GDP are second only to Illinois among the 10 leading technology states (same as footnote 15). Massachusetts per capita income in 2007 was over 17 percent higher than the national average up from 13 percent in 1997 (*Index of the Massachusetts Innovation Economy* 2008: 4).

While home to few Fortune 500 industrial enterprises, Greater Boston has enjoyed a persistently high level of R&D expenditure. The John Adams Innovation Institute estimates that Massachusetts trails only Sweden in business R&D investment per GDP averaged over the 1999-2004 period.[18] The state's percentage of gross (private and public) expenditure on R&D to GDP of over 5 is the highest amongst states in the US and considerably higher than in leading countries such as Finland of 3.4 percent, or in fast growing, technology following countries like Ireland's 1.2 percent

Why the large gap between the academic perception of decline of 'Route 128' and the reality?

The decline of Route 128 viewpoint conflated the business model and technology trajectory of a single sector with the dynamic processes of a diverse population of high tech companies. In fact, we find a virtual 'manufactory of species' to use Darwin's expression but applied to sectors.

---

[17] See www.neweconomyindex.org/states for different years.

[18] As measured by business expenditure per $10,000 GDP, Sweden was first in the world at $301 over the period 1999-2004; Massachusetts at $281 was second followed by Finland at $234. Industry funded R&D in both the most developed and rapidly growing economies tends typically accounts for approximately 60% to 75% of gross R&D expenditure (*Index of the Massachusetts Innovation Economy* 2007, John Adams Innovation Institute, Massachusetts Technology Collaborative; data sources are S&P Compustat and OECD ANBERD databases).

While minicomputers was the largest, its collapse was mitigated and transcended by the rapid growth of other sectors including data storage systems, semiconductor equipment making, telecommunication switching equipment, robotics, business software tools, mutual funds, medical devices, pharma and biotech, advanced materials, computer games, and renewable energies.

The decline of Route 128 perspective misses what is perhaps most interesting about the region's high tech economy. It is the result of struggle between two rival and overlapping regional business models in which the open-system model has dominated the closed-system model. The region is home to a constantly evolving population of more than 3000 high tech business units.[19] This number represents business units that engage in R&D and seek to establish a **novel** technology platform.[20]The open-system model has proven highly protean; its origins go back to the early days of Massachusetts' business and industrial organization.

The role of the federal government was central to both business models with respect to funding of R&D. Nevertheless, the growth of many of this diverse range of sectors is not about technology transfer from the region's universities; but it is a story of specialized companies leveraging the region's S&T infrastructure and knowledge base. These are not the same. Many rapidly growing sectors cannot be attributed to R&D results of the region's federally funded labs.

The example of Greater Boston's medical device industry over the period from 1990 to 2003 is shown in Table 1. Five other fast-growing big medical device companies and twelve other fast-growing, mid- to large size, non-medical device companies that also make medical device products are identified in the same study for the same time period (Best 2009). Perhaps not surprising over 20 foreign headquartered mid-and big fast growing companies also participated in the growth of Greater Boston's medical device industry (Best 2006).

The proposition is this: Greater Boston's shifting population of high tech enterprises has demonstrated a collective capacity to rapidly reconfigure to develop new technologies, grow new companies, and foster the development of new high tech sub-sectors. The origins and growth of these sectors do not fit the technology transfer combined with vertical-integration business model as illustrated by the minicomputer industry. A parallel open-system business model and corollary distributed innovation system were simultaneously achieving critical mass in Greater Boston. While obscured by the successful growth and size of the minicomputer giants, the origins of both innovation systems can be traced to the emergence of high-tech companies in the early postwar period. The origins of the open-system business model, in contrast, goes way back in the region's history.

---

[19] The number 3000 is a conservative estimate. Rosegrant and Lampe write that in 1965 there were 574 companies along Route 128; by 1973 the number was 1212 and by the mid-1980s nearly 3000 high tech companies existed in Massachusetts (1992: 130-132). CorpTech's directory contains in excess of 3000 throughout the 1990s. Mass High Tech Directory has over 5700 listings but they include many that do not develop as distinct from use high tech products and services.

[20] According to CorpTech data for 2003, Massachusetts had 3736 high-tech business units broken down as follows: private—independent companies 2578 (69%); units of private—independent companies 253 (7%); public—independent companies 237 (6%); units of public—independent companies 318 (8.5%); units of non-US headquartered companies 283 (8%); independent partnerships 22 (0.5%) and non-profit independents 45 (1%).

The origins of a large population of specialized SMEs in manufacturing in Massachusetts can be traced back to the establishment of the 'American System of Manufacturers' in the first decades of the nineteenth century. That heritage exists today in the form of a critical mass of companies in tooling, instruments, and equipment making. In fact, these companies as a group, most of which are SMEs, have evolved into an 'advanced manufacturing' infrastructure for the region's high tech enterprises (Best 2009). But the term high tech and the region's large population of high tech enterprises are intertwined with the creation of America's postwar science and technology infrastructure.

The local imprint of the federal S&T system was evident in the early days. The term high-tech was first used in the late 1960s to describe 'science-based' or 'scientist-entrepreneur' companies and government sponsored labs along Boston's Route 128. One contemporary observer estimated some 690 such entities fit the description: "It is not clear whether the name [high tech] derives from the high technologies flourishing in the glass rectangles along the route or from the Midas touch their entrepreneurs have shown in starting new companies. Maybe both" (Lieberman 1968). Lieberman writes that the key to the success of the companies located on Boston's "Golden Semicircle…is due to '**uniqueness'** of the average company's technology…and the availability of government contracts during the early years" (referring to a 1960 study by Roberts in Lieberman).[21]

A key to the success of the evolving population of high tech enterprises in the Greater Boston area was the central role of third-mission, research-intensive universities in the region's industrial system. But not only, or even primarily, because of technology transfer as in the case of DEC. The open and public availability of scientific and technological research is integral to the ideal of the university and the advance of knowledge. The goal of open research is in conflict with the drive by companies for intellectual property rights. Mission-funded research by government departments is often ambivalent. Regions without strong university leadership will be more likely to be complacent with respect to the importance of open research and as a consequence the pressure for secrecy and a closed and increasingly concentrated business system will more likely dominate.

As noted, the role of the federal government was central to both with respect to funding of R&D. Hanscom Air Force Base and its co-located FFRDCs, Lincoln Labs and MITRE Corporation, became the late twentieth century functional equivalent to the Springfield Armory of the first half of the nineteenth century. But whereas the Armory developed and implemented the principle of interchangeability, Hanscom developed and implemented the principle of systems integration. In both cases, federal government investments in leading technologies fostered the development of an open-systems business model. In both cases a population of specialist companies were

[21] A useful exaggeration is to think of the high tech business enterprise as centered around two teams: a technology integration team and a business development team. A technology integration team is the organizational or institutional means to combine the expertise of a range of scientific and engineering disciplines all of which are required to develop and support distinctive technology platforms. The challenge is that every discipline has its own language, concepts, and perspectives and communication across disciplines is both problematic and critical to success. The business development team has the challenge of transforming a fledgling company with a novel technological idea and facing several years of zero sales revenues into a fully developed, growing entrepreneurial enterprise under the pressure of time. These themes are elaborated in Best (2009).

established that both drew from and advanced the region's technologically-advanced knowledge base and skills. Whereas the American System of Manufacturing was diffused by a community of machinists, the Boston System of High Tech was diffused by a community of scientists and engineers (Meyer 2006; Thompson 2009. Both were open systems involving publically available research.

In both cases the role of the federal government was an inadvertent industrial policy that established a basis for regional competitive advantage. For the Armory it was the principle of Interchangeability; in the case of the post-World War FFRDCs and Hanscom Air Force Base it was the principle of Systems Integration.

In the process of developing advanced technologies funded by the federal government greater Boston was bequeathed a knowledge base in the form of a huge talent pool of scientists and engineers with practical research experience in an emerging technology. Ken Olsen was not the only engineer/entrepreneur who seized the opportunity to build high-tech companies. Rosegrant and Lampe, and Edward Roberts (1991) provide details on hundreds of companies that were created to develop technologies traceable to the region's FFRDCs. Many transitioned from small scientist-entrepreneurial companies to sustainable business enterprises employing dozens if not hundreds.[22]

Each nonprofit lab (and BB&N) pursued and drove a technology trajectory and had a similar precipitating effect on regional growth dynamics. The important point is that these labs were associated with the creation of a diverse population of technologically specialized enterprises as distinct from precipitating a limited number of future Fortune 500 companies. More than fifty companies can be traced to Lincoln Labs. The Instrumentation Lab at MIT became the Charles Stark Draper Laboratory, an independent, nonprofit R&D company in 1973. Rosegrant and Lampe estimate that fifty-five companies have spun off from the Instrumentation/Draper Laboratory. Roberts traces 129 companies to 3 MIT departments. Some of these companies have themselves been virtual company incubators as well: While DEC would be the leading example, EG&G has some 15 daughter and 58 grandchildren companies. According to a 1997 MIT/BankBoston study, MIT graduates had started 4000 companies nationwide and 1,065 in Massachusetts and the later accounted for a quarter of manufacturing exports from the State.

The open-system business model, in contrast to closed systems, converts the region's business enterprises into a resource in the form of a vast system of inter-firm connections that can be drawn upon to enhance innovation and industry development. Three thousand high tech companies means not only 3000 technology integration teams but 3000 science advisory boards and 3000 board of directors. Inevitably, there will be overlap of individuals on both boards cutting across companies. Brown and Duguid (2000) have examined the function of "communities of practice" made up of professional communities that form informal networks

[22] At any one time the ESC may be managing a dozen or more C^4I programs. The ESC's biggest contracts go to the nonprofit research laboratories such as Lincoln Labs, the MITRE Corporation, and Carnegie Mellon and to the major defense contractors such as Raytheon, Grumman Aerospace, Boeing, Loral, Rockwell, and Marconi. But the ESC also manages dozens of contracts even in the $1 million to $3 million range. In fact, Hanscom draws upon over 2000 small business firms that specialize in software development, telecommunications, radar, satellite communication, space technology, electronic sensors, and information management. Many are in the Route 128 area.

independent of an individual's company (Maskell and Malmberg 2007). Chemical engineers, for example, that went to the same university and/or once worked for the same company or who happen to be members of the same sports club will form an informal 'community of practice'.

The density of such overlapping and shared inter-personal relationships becomes a resource for problem-solving in an open-systems business model for existing firms. But it can also facilitate the rapid creation of new teams and firms seeking to exploit emerging technologies and market opportunities. The rate of new firm creation is extremely high in Greater Boston and so, too, is the churn as many aspiring new companies are not successful. In this Shumpeterian process of creative destruction conducted at the regional level, growing firms can acquire productive resources from declining firms.

The ongoing process of creating new firms and growing firms is an institutional vehicle for increasing technological specialization and differentiation within the population of companies. This resonates with Adam Smith's law of increasing division of labor but applied to increases in the differentiation of technological capabilities of firms. Increases in the division of labor within and across firms contribute in the words of Adam Smith to "improvements in the arts". It is the basis for Adam Smith's discovery principle and his theory of innovation (Loasby 1999). It enables and benefits companies that focus. Firms that focus on core capabilities and partner or network for complementary capabilities can devote more time, energy, and resources to each company's distinctive technological capability and the drive to advance it.

Consequently, Greater Boston has come to be home to a technological full-house in variety which has created yet another important feedback effect on innovation. A population of diverse high-tech companies creates potential for innovations as a consequence *"unplanned confluences* of technology from different fields" (Kostoff 1994: 61). However, in Kostoff's words "an advanced pool of knowledge must be developed in many fields before synthesis leading to innovation can occur".

In recent years Greater Boston has been the side of a huge growth in the life science industries of biotech, pharmaceuticals, and medical devices. And no region has been a bigger recipient of research funding from the National Institutes of Health. Again, the region's academic excellence, in this case medical education within a complex of research-intensive hospitals, has formed a three-way, mutual symbiotic relationship with the national S&T infrastructure.

In each of these cases the ongoing interactions amongst the government funding agencies, university administered R&D, and technology-driven companies combine to foster and replenish a region knowledge base. This knowledge base, in turn, is a both a resource for new firm creation and a magnet that attracts research departments of firms located elsewhere.

The inward investment in Massachusetts also contributes to the process of regional knowledge base development. In fact, 69 of the 200 largest employers are headquartered out of state (examples include IBM, HP, Microsoft, J&J, Cisco major employers). Roughly 8-10 percent of the State's 3000 high tech business units are foreign headquartered, attracted to Massachusetts because of the region's distinctive knowledge base.

This knowledge base has deepened and widened not only via the national S&T infrastructural investments but it is integrated into and with the region's open-system business model. The open-system can have major advantages (Kay 2009). First, experiments are multiplied and design are decentralized and diffused across a population of independently managed companies. Second, successful experiments attract resources and are quickly imitated; failed experiments conducted in small or medium-sized enterprises take the form of rapid exit. Third, disruptive innovations usually come to the market by new entrants (Christensen 1997).

State level policymakers played only a small role in the early days of the establishment of the Boston area's business system and research-intensive university complex. But this changed. Since the crash of the minicomputer industry in the mid-1980s, the State's policymakers have been successful at fostering technology-based economic development initiatives that combine national funding and leadership in emerging technologies and sectors. The Massachusetts Technology Collaborative has set a standard for developing and measuring high tech innovation success indicators for policymakers at the state and local level.

Part Five. High Tech without Innovation: Greater Washington's Closed System Business Model

(please ask author for this section; it is not included here to meet word limit)

Part Six: Observations and Implications

Cyril Henshelwood, President of Royal Society, eloquently captured a theme of this paper in 1960: "The intercourse in terms of the equality between these different estates [government, industry, and academy] of the nation is like a sensitive nervous mechanism endowing the community which possesses it with capacities and potentialities realizable in no other way. The subtle coordination of the academy can no more be replaced by a bureaucratic organization or a system of economic incentives and deterrents than the integrally involved biological controls of a living organization can be replaced by crudely devised mechanical appliances".

Other nation states, particularly interwar Germany were the first to understand the military and industrial potential of science. But whereas the German state subordinated science within a single hierarchy, the American model established a three-way, mutually symbiotic system that coordinated elements of the state, science and industry. Critically, the ideal of the university to the pursuit of science independent of the goals of the State and of industry was not sacrificed.

The 'capacities and potentialities' of the three branch system were dramatically revealed by the Vannevar Bush-led OSRD directed to create and scale an advanced-technology weapons industry. Greater Boston was an ideal location to make it work. The region had MIT, the pioneer in establishing industry/university partnerships in designing and developing technology-advanced products. It was also home to an easily overlooked 'industrial district' of tooling, instrument, and equipment making companies that collectively exhibited the highly flexible production capabilities to do prototyping and pilot production lines that could be scaled to volume production in plants, located elsewhere, with process engineering capability.

Bush, as an insider in all three branches was exceptionally well placed to orchestrate the **triangular relationships** that cut across the three branches. The branch-specific resources could thereby be integrated in an entirely new way to build the organizational capabilities into what became the nation's advanced technology weapons industry. The triangular relationships are not about combining or reassembling already existing resources; they are about establishing interface rules by which new relationships could be formed to build capabilities that leverage the contribution of each to the productivity of the system as a whole. In this, Bush was a systems architect who designed systems at the inter-organizational level but with awareness of systems engineering at the technological and production levels.

Systems integration has locational implications. To build the triangular relationships and organizational capabilities, the OSRD went to the home bases of the scientists most knowledgeable about the science of the emerging advanced technology weapon systems. These scientists, in turn, needed to work hand-in-hand with design and production engineers in the nation's instrument, tooling, and equipment making companies. The Boston area was a magnet as it was a location that had both types of necessary inputs. It meant that the government's emerging S&T infrastructure was organizationally integrated with regionally specialized R&D and production facilities.

Thus Boston came out of the War with a much enhanced regional knowledge base much of which was intangible as it was embodied in the labs and production facilities, public and private, and the skills of the community of scientists and engineers and their inter-relationships. The regional knowledge base became a regional competitive advantage in the attraction of governmental funding for each new technology systems from computer to air defense systems, to the Internet. The dynamic consequence was that with every new advanced technology project defined and funded by the government, the local combined knowledge base of the recipient university and companies was deepened and widened.

The decline of Route 128 perspective underestimated the dynamic processes by which technologies evolve in the process of sectoral transition. From an evolutionary sector perspective, new sectors grow out of old sectors ("descent with adaptation). For example, computer technology in Greater Boston did not end with DEC and the crash of the minicomputer industry; computer development was central to Greater Boston's leadership in successive generations of air defense systems. It evolved in the process.

The claim is not that the United States government intentionally undertook a business development role. It did not. The claim is that the rise of US industrial leadership in high tech industries cannot be explained without accounting for the role of the federal government jointly with that of the third-mission, research-intensive university system. The triangular relations shaped the new open-system business model which at its best fostered the development of regional populations of increasingly differentiated entrepreneurial enterprises which collectively over time exhibit new sector emergent properties. However, the business development dynamics were neither direct nor planned. And they are not simple.

Company size profiles (population demographics) of the rapid growth phase of medical device, telecommunication, software business-tool sectors in Greater Boston follow a similar pattern: the proliferation of mid-size, growing firms which collective generate a process of increasing technological differentiation.

Hence the idea of the developmental-state role is of fostering regional knowledge bases and skill formation processes that in turn are productive resources for the creation and growth to size of entrepreneurial enterprises. Once in place, self-organizing properties emerge as a consequence of a population of increasingly technology-differentiated enterprises and the co-evolution of business development infrastructures.

While Greater Boston is the paradigm case of the emerging regionally decentralized, American System of High Tech, Silicon Valley was a west coast version. Like Greater Boston, it too had a prewar regional capability in tooling, instrument, and equipment making companies (Sturgeon 2000; Lécuyer 2006).

The Boston System of High Tech is different from that of Silicon Valley and offers insight into non-direct forms of inter-firm relations and extra-firm infrastructures in a dynamic system with the capability to generate new sectors. Silicon Valley is an open-system business model with a strong vertical specialization dimension. The semiconductor and personal computer industry, for example, has numerous vertical links in the supply chain; this is less so in Greater Boston (Kenny and von Burg 1999). This means in Silicon Valley, the existence of a vertical chain with many links, that a new entrant to specialize in one link only and plug into an existing value chain by simply partnering within a range of preexisting networks.

In the case of greater Boston we find, instead, infrastructures that fulfill a functionally equivalent role to interface rules along an extended, vertically specialized supply chain. In this paper, the focus is on an S&T infrastructure which is defined to integrate the national and regional into a local knowledge base. This knowledge base is critical to the open-system business model; they depend on one another. The open-system business model depends and thrives on the existence of extra-firm infrastructures. Others, besides the S&T infrastructure, are the tooling, instrument, and tool making infrastructure and the business organization development infrastructure (Best 2009). These are the functional equivalents to the infrastructures internal to the large, multi-divisional company the drove the second industrial revolution.

The Greater Washington high tech industry illustrates just how critical it is to develop the triangular relationships and the role of the community of scientists and the university in developing a regional knowledge base. Without the presence of a strong research-intensive university in the greater Washington region, the shared tendency of military and private business to trade-secretive and closed research practices will likely prevail. The result, at least in greater Washington, has been the reinforcement of a closed-system model of business organization. Instead of a triangular relationship of the open system business model we find a murky-world triangle of government-businesses, government agencies, and lobby-influenced politicians.

It did not have to be. The major lesson from the comparison of Greater Washington and Greater Boston is the protean impact on business organization of the principle of open research driven by a regionally powerful, third-mission, research-intensive university.

What distinguishes northern Virginia is the lack of a regional capability to create new industries. This is not caused by the lack of a research-intensive university per se, but the consequences of the demise of an independent role of science on business organization. Contracts from agencies of the federal government even on the massive scale of northern Virginia are not sufficient to foster a dynamic, technology-driven regional economy.

While the business development role of the state does not figure in economic theory or macroeconomic policy discourse it has long been integral to the art of statecraft.[23] This has contributed to a failure to distinguish between developmental and 'corporatist' roles of the American state. Moreover, without explicit treatment, the developmental role is not coordinated with conventional macroeconomic policy and they can work at cross purposes with deleterious effects on both.

[23] Ironically, the developmental role of the state is understood implicitly in state government economic policymaking circles as they compete for federal funding of research and education. Technology-based economic development initiatives nearly always involve partnering relationships amongst leaders of local economic development agencies, research-intensive universities, technology-led enterprises, and federal government research funding agencies.

Table 1

Fast-growing, Mid-size Medical Device Companies: Employment

Companies	Founded	1990	1995	2000	2001	2002	2003
Lifeline Systems, Inc.	1974	250	325	620	790	850	850
Inverness Medical Innovations	1992	-	78	419	704	800	800
Hologic, Inc.	1985	130	170	600	839	780	750
Nova Biomedical	2001	475	500	500	664	665	665
Cytyc Corp.	1987	25	55	200	495	495	626
Zoll Medical Corporation	1980	150	275	390	430	585	844
Gentex Optics, Inc.	1932	120	250	500	500	500	500
Candela Corp.	1970	174	180	285	285	300	325
Clinical Data	1972	9	80	175	285	151	302
Biopure Corporation	1984	40	110	180	173	240	240
ABIOMED	1981	55	70	182	265	264	238
Aspect Medical	1987			100	200	230	205
American Medical Instruments	1975	60	145	145	149	149	195
Hologic/Lorad	1989	150	280	350	350	275	
Summit Technology	1985	60	211	425	Acquired by Nestle SA		
MediSense	1981	60	850	Acquired by Abbott Labs. In 1996			
NMC Diagnostics	1971	140	250	Acquired by Fresenius AG in 1998			

Source: vTHREAD

Source: Best (2006)

Table 2

			Innovation Indicators					
	Boston		**Washington**		**Silicon Valley**			
High Tech Employment	526,000	*Second*	426,000	*Third*	629,000	*First*		
	MA		**VA**		**CA**			**US**
Per capita Fed R&D (2004)	$827	*Second*	$829	*First*	$503			$337
Gross R&D GSP (2003)	5.26	*First*	2.49		4.15	*Second*		2.68
Corp. R&D per $1000 sales (2005)	$82	*First*	$3		$78	*Second*		
Venture Capital (2004)	$2,847M	*Second*	$265M		$10,270M	*First*		
Patents per capita 2003-2005	59	*First*	15		59	*First=*		31
Ave. growth of Manu. Xs 2001-2005	6	*First*	1.2		2.3	*Second*		5
SBIR awards per 100,000 people (2005)	12	*First*	5	*Second*	3			

Source: Index of the Massachusetts Economy, Massachusetts Technology Collaborative, John Adams Innovation Institute, 2006 and 2007.

Table 3

Deloitte Fast Growing High Tech Companies 2002-2006						
	Maryland	**Virginia**	**Massachusetts**	**Silicon Valley**	**Los Angeles**	**San Diego**
Biotech/Pharmaceutical	**4**	**-**	**10**	**8**	**1**	**4**
Communications/Networking	**5**	**3**	**6**	**12**	**3**	**4**
Computers/Peripherals	**-**	**-**	**-**	**1**	**3**	**2**
Internet	**1**	**1**	**4**	**12**	**9**	**-**
Media/Entertainment	**-**	**-**	**1**	**2**	**2**	**-**
Medical Equipment	**-**	**-**	**5**	**7**	**5**	**2**
Sci/Tech Instrumentation	**-**	**1**	**4**	**5**	**3**	**2**
Semiconductor	**-**	**-**	**1**	**14**	**3**	**-**
Software	**8**	**19 (def.?)**	**11**	**8**	**7**	**3**
Total companies	**18**	**24**	**42**	**69**	**36**	**17**
Total sales ($billion)	**0.8**	**1.2**	**6.4**	**47.9**	**4.6**	**1.9**

Source: Compiled from 2007 Deloitte Technology Fast 500 covering the 2002-2006 period.

Table 4. Concentration Ratios

Changes in Concentration Ratios (% arms sales of combined total of SIPRI Top 100 Companies, 1990-2005)

	1990	1995	2000	2005
5 Largest Companies	22	28	41	43
10 Largest Companies	37	42	57	62
15 Largest Companies	48	53	65	69
20 Largest Companies	57	61	70	74

Source: SIPRI, Stockholm International Research Peace Institute

References (please ask author for references; not included here to meet word limit)