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Lowell's Industrial Regeneration: Dynamic Technological Capabilities[1]

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In this paper, I tell a story of Lowell, Massachusetts not as a textile city, but as part of a multi-industry, high-tech region with a technology genealogy that goes back to the early days of the state as an instrument-making region. I attempt to define, make operational, and measure the concept of dynamic technological capabilities at both the enterprise and regional levels. Capabilities are what enable firms to create new products and processes in response to new market opportunities. By building a database of technology producers in the Lowell area we can infer the cumulative process by which technological capabilities are developed over time. The database of enterprises includes product portfolio and employment for the period from 1986 to the present and, most important, the date of enterprise founding. I also tell a post-textile story about the industrial dynamics of the Lowell region and focus attention on firms and technologies that are obscured by standard industrial classification codes.

Lowell, Massachusetts, is America's first industrial city. For the first 150 years of its existence, it was known as a textile city, but one in decline for nearly 100 of those years. "In 1880 more than one-half of all textile workers in the country…were employed in New England…."[2] In the long process of textile decline in New England, Lowell suffered. This is not remarkable; what is remarkable about Lowell is that it has bounced back. It is no Sheffield, England, or Detroit, Michigan.

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[1] This paper has benefited materially from inputs from research assistants on the Anticipating Technology Trend project from which this paper is drawn, including Albert Paquin, Hao Xie, Heath McKay, and Ed March.
[2] Joshua Rosenbloom, "The Challenges of Economic Maturity: New England, 1880-1940," in *Engines of Enterprise: An Economic History of New England*, ed. Peter Temin (Cambridge, Mass., 2000), 155.

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Wang led Lowell's regeneration as a high-tech town in the late 1970s. However, it was relatively short-lived. Once an employer of 30,000 in Lowell it has long since passed out of existence.

The unexpectedness of the Wang-led revival and the severity of the regional downturn of the late-1980s led observers to explain the Wang years in terms of serendipity, Cold War defense expenditures, and more or less treated as a one-off accident of history. However, after a period of decline in the late 1980s, Lowell again unexpectedly enjoyed a sustained economic revival in the 1990s. This has been explained, when acknowledged, by the Internet bubble and "dotcom" mania. Once again, the default account of Lowell and the surrounding region is one of structural loss of competitiveness.

These accounts, I argue, obscure more than they reveal about industry in Lowell today. In fact, within Lowell and the adjoining townships of Chelmsford and Westford, there are over 150 business enterprises that make highly specialized technology products. These enterprises are hidden from view, not only from existing histories of region, but from economic analyses, newspaper accounts, and political discussions. They are unknown locally, but well-known by technological communities in Silicon Valley, Asia, and Europe. In fact a sizeable percentage of them are operating units of enterprises with foreign and Silicon Valley headquarters, and more than a quarter of these export over 25 percent of their products and services.

I tell a story of a multi-industry, high-tech city with a technology genealogy that goes back to the early days of New England as a vibrant industrial region. Why does this account of Lowell have to be told? Why, even to most observers in Massachusetts, does this story stretch credulity? The answer, in part, lies in how we conceptualize and measure industry, technological change, and innovation.

Industrial Districts: The Dynamic Capabilities Perspective

There are three conventional approaches to industrial geography or the regional concentration of industry: the neoclassical story of increasing returns or Marshallian externalities, the Porter "diamond" story, and Saxenian's account, which focuses attention on institutions of cooperation.[3]

These accounts are all static accounts of competitive advantage. The terms "technological change," "innovation," and "industrial development" can be found in all three accounts, but they are add-ons to

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[3] Paul Krugman, *Geography and Trade* (Boston, Mass., 1991) summarizes the neoclassical account of regional specialization in the Marshallian threefold distinction amongst three types of externality. Two are pecuniary: sufficient production to benefit from scale economies of intermediate producers and a thick labor market. The third is technological in the form of spillover benefits of "ideas."

inherently static conceptual frameworks. I begin and end with a capabilities approach to understanding industrial districts. Perhaps I should say a Penrosian account of capabilities, because her account is inherently dynamic.

The starting point for a dynamic theory of industrial development is the business enterprise and the central organizing concept is capability.[4] The source of business success is the development of unique, hard to imitate capabilities. Dynamic capabilities are the "organizational and production methods and tacit knowledge that enable the firm to create new products and processes in response to changing market opportunities."[5]

Manufacturing, from this perspective, is not simply about making widgets; it is about the development of capabilities to create new products and processes in response to changing market opportunities. New product capability requires integration of manufacturing and services, not their separation, a presupposition of official industrial classification systems. By traditional static notions of manufacturing, very little occurs in Massachusetts and Lowell. The region and sub-region have gone through processes of de-industrialization, especially as measured by high volume production of consumer goods. However, from a capabilities perspective, Lowell is part of a vibrant, technologically diverse industrial region of unique new product development, technology management, and innovation capabilities. I focus on technology products and technological capabilities.

History is central to the capabilities and innovation perspective that informs this research agenda. Why? We care about history because a region builds on what it has and if you do not know a region's history you do not know on what to build. There may be no better place to carry out historical research on technological and industrial change than Lowell.

A Technology Classification System

If dynamic capability development, at the level of the firm and the region, is the critical variable in explaining regional competitive advantage we have a measurement problem. Official statistics were designed for different purposes.

The Limits of SIC and NAICS. The U.S. standard industrial classification (SIC) system has been criticized for its lack of a single concept by which to

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[4] I developed these ideas in *The New Competitive Advantage: The Renewal of American Industry* (Oxford, U.K., 2001). Chap. 5 is a case study of Massachusetts.

[5] David Teece and Gary Pisano, "The Dynamic Capabilities of Firms: An Introduction," *Industrial and Corporate Change* 3 (1994): 537-56, 514.

distinguish products, sectors, and industries.[6] Some sectors were defined in terms of production (supply) and other in user (demand) criteria. The SIC was also criticized for being based on economic "structures" of the 1930s which were no longer relevant to the economic structure of modern times.

The North American Industry Classification System (NAICS) was established to overcome these objections. It is based on a "production" concept and the sectors have been revamped to better represent the modern services and information-intensive features of the U.S. economy. While NAICS addresses certain criticisms of the SIC code, it does not provide a classification system that captures the industrial dynamics of technologically-advanced regions for several reasons.

First, like the SIC system; NAICS conforms to disclosure rules that force suppression of information at the local level. In fact, the more refined classification system only increases the problems facing users wanting information about what is happening to manufacturing in a region.

Second, NAICS' concept of production is static. NAICS, unlike the SIC codes, is based on a single concept classification system, production activities. However, that production is itself a target of strategic activities. For example, firms with new product development capability pursue concurrent engineering which involves the redesign of product and process; increasingly, high-tech manufacturing demands the development of technology management capabilities, the sole purpose of which is to alter production activities.

Third, NAICS' concept of business organization obscures specialization dynamics. While the NAICS hierarchy goes to 6 digits (versus 4 for SIC) even here the criterion seeks to obscure specialization; product specification remains general because it is assumed there are numerous sellers of the same product. While this is the case in many, especially commodity industries, the "focus and network" business model that drives high-tech manufacturing and technology producers and the "open-systems" in which they operate is established so that firms can

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[6] SIC was developed by an Interdepartmental Committee on Industrial Statistics, established in the 1930s by the Central Statistical Board of the United States. The Interdepartmental Committee on Industrial Statistics was created "to develop a plan of classification of various types of statistical data by industries and to promote the general adoption of such classification as the standard classification of the Federal Government." The purpose was to develop a uniform system for recording and measuring economic activities for use by the various agencies of government that collect and assess economic data. The list of industries for manufacturing was first published in 1938 followed by the list for "nonmanufacturing" industries in 1939 that, together, constituted the first Standard Industrial Classification for the United States; **www.census.gov/epcd/www/naicsdev.htm**.

achieve business success via developing unique technological capabilities to create unique products and services.

Fourth, while NAICS disaggregates services to better reflect modern economies, the fundamental separation between manufacturing and services establishments obscures business and industrial organization in high-tech regions. For example, most successful technology companies in the Lowell area have products that are classified in both manufacturing and services categories. A classification system that obscures this central feature of industrial success is misleading.

The assumption of price competition as the determinant of market success was consistent with the assumption that economic activity could be separated into either manufacturing or services activities. However, the reality of product-led competition forces firms to develop new product-development capabilities that involve the integration of manufacturing and services.

All classification systems illuminate as well as obscure, and each is anchored in an economic theory. Neoclassical assumptions about production, business organization, and price competition, anchor the production-based classification system.[7] These are too general for understanding competitive dynamics and the sources of growth and decline at the regional level.

SIC systems' conceptual and measurement problems increase when applied to technology products. For Massachusetts, in particular, understanding industrial dynamics must account for distinctive technological categories. The region's industrial success depends upon the development of next generation technology products.

A Capabilities Classification System

The first requirement of a classification system, from a capabilities perspective, is that the system account for the cumulative and collective development of unique capabilities. A second requirement that may be exclusive to the Lowell area is that the classification system take account of technology producers and capture the level of detail required to indicate capability specialization.

The challenge for a capabilities perspective is clear: capabilities are neither observable nor measurable. Fortunately, over time firms and the portfolio of products they make are observable and measurable.

Therefore, a perspective in which capabilities (organizational, production, and technological) are the critical dimensions of variation,

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[7] Both the SIC and the NAICS systems reflect the premise that the economy is composed of industrial sectors made up of organizationally simple and isomorphic firms that sell homogeneous products and compete on the basis of price, not product or process. Change occurs in processes but simultaneously across all firms in the industrial category.

focuses attention on the industrial enterprises that populate a region as the engines of capability development and the drivers of regional growth.

To better understand the sources of industrial success in Lowell, and Massachusetts, we have developed a database of several thousand operating units of technology-producing companies. The distinctive feature of the database is the technology classification system. It is designed to pick up firms that fit into one of 18 technology categories, regardless of size and type of ownership. *CorpTech*, which began publication in 1986, designed the technology classification system. We combine the *CorpTech* directory with other directories, such as *Mass High Tech: the Journal of New England Technology*, to construct a database that includes over 12,000 operating units in Massachusetts and surrounding states. *CorpTech* only provides current directories. It is a challenge to construct historical series.

As a part of this larger project, we have constructed a historical series for Lowell and two adjoining townships of Chelmsford and Westford (herein referred to as "the Lowell area") for the 1986 to 2003 period. This directly covers the severe downturn of 1986-1992 and the Resurgence of 1992 to 2000. However, indirectly, we can go back further because we have the date of establishment of all of the enterprises in our database.

The database allows us to look at companies to find technologies being produced, when they were established and if they are still operating at present. As an example, **Chart 1** shows the year established and technology class for all of the currently operating companies in the CorpTech database for the Lowell area.

With respect to technology producing companies: These are primarily companies that produce capital goods as distinct from consumer goods or intermediate inputs. Thus, technology producers are not, in general, supplying parts, components, sub-assemblies to final assemblers; technology producers are not part of the consumer goods supply chain. Our database captures operating units that make technology products; it does not capture the stock of technology or the flow of material and parts along a supply chain.

Concerning the technology classification system: the classification system is anchored in distinctive branches of engineering knowledge. It is a classification system that makes sense to engineers much as standard industrial classification systems make sense to economic accountants. The technology classification system, like a botanical one, seeks to develop a single system in which all technology products can be classified. The definitions are pragmatic, they are based on what engineers do, and the knowledge base they draw upon and contribute to.[8]

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[8] If there were ethno-engineers, we could also refer to studies of distinctive engineering communities such as mechanical, electrical, power, chemical, plastics, software, systems, etc., and note that the distinctions made and

Technology capability, as noted, provides competitive advantage and business success based on the development of unique, inimitable capabilities; the idea of technology capabilities captures the technological uniqueness of a company and region's development. Technological capabilities are the specialized engineering practices and knowledge domains that support, constitute, and in many cases define a company's competitive advantage. Technological capabilities are invisible; unlike technology products, they cannot be purchased in the marketplace. Capabilities, whether organizational, production or technological, take time and experience to develop.

Our database does not measure technology capability directly because technology capability, like all capability, is invisible. We are not observing capability directly but at the stream of products generated by capability. Because a stream of products covers a period of time, we can infer the underlying capability that generates the stream. Capability takes time and experience to develop. It is an outcome of an endless iteration between specialist capability and ever-changing market opportunity. By focusing attention on surviving operating units we identify a population of companies that, with further analysis, allows interpretation and assessment of a company and region's distinctive capabilities.[9] The method starts with sorting the survivors by the technology code of the products they make.

Technology Producers in Lowell-Chelmsford-Westford

Chart 2 shows employment today by technology product category in Lowell-Chelmsford-Westford (LCW or the Lowell area) over the 1986 to 2002 period of the companies that are still operating in 2003. It illustrates the extraordinary role of Wang's location in Lowell in 1978 and it rapid growth. Wang Laboratories employed over 30,000 in 1986. After a series of acquisitions, Wang Laboratories, Inc. became a subsidiary of Getronics, a Dutch company located in Billerica that employed 6,500 in 2000.

Chart 3 removes computer hardware to draw attention to the composition of other technology producers in the Lowell area. What can we say about the region's technological capabilities? The first step is to examine the leading firms and characterize the technology products they design and make.

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categories developed were specific to the activities that constituted that livelihood of each community.

[9] The capabilities perspective is developed in the author's *The New Competitive Advantage*. Economic development is about the development of organizational, production, and technological capabilities. The focus of this paper is on technological capabilities. As will become apparent, all three types of capability are closely interrelated.

Table 1 includes the 70 technology-producing firms with over 25 employees that are operating in the Lowell area in 2003. They have been organized into distinctive technology domains based on an analysis of their place within the technology classification code. Figures 1 and 2 refer to the primary classification, defined as the technology product that accounts for over 50 percent of company sales. Table 1 classes the same company based on an analysis of their primary, major, and minor codes. The idea is to interpret technology capability and identify attributes of regional specialization.

Three Periods in Lowell's Recent Technological History

Table 1 is broken into 3 periods: the pre-Wang (or Massachusetts "Miracle" beginning in the mid-1970s), the Wang era (roughly 1975-1985), and the post-Wang or Internet era of the 1990s. Business units that are operating today (the survivors) are grouped according to technology product in the sequence of their founding. The result is 13 technology groups slotted into one of the three periods depending upon the earliest founding date of a firm in the group. Thus, each firm is located within a technology trajectory that begins in the pre-Wang, Wang, or post-Wang era. For example, M/A COM, a microwave integrated circuit maker founded in 1958, is a leader of a technology trajectory of nearly 50 years that includes at least 3 presently operating firms in the Lowell area.

The intention is to illustrate the central idea of dynamic technological capabilities at both the enterprise and regional levels. We are investigating firms because firms are the developers and carriers of distinctive technological capabilities. As noted, capabilities are what enable firms to create new products and processes in response to new market opportunities. Thus by looking at the evolution of product portfolios, we seek to infer the cumulative process by which technological capabilities are developed over time. A technology trajectory, in this exercise, is an inferred scan of successive iterations in the development of technological capabilities within a single or group of regionally co-located enterprises.

These firms can be said to contribute collectively to the region's underlying technology base or techno-ecosystem. Further, we can think of a regional innovation system as the institutional infrastructure, including the range of specialist capabilities of a region's enterprises that replenishes and reinvigorates the technology base of the region.

Pre-Wang Years (Lead Companies Established before 1977)

Wang relocated to Lowell in 1977. "Wang's greatest gift to Lowell was its address." This is a quote from William Taupier, the Lowell city manager who facilitated the re-location of Wang to Lowell in 1977.

The largest category in terms of numbers of firms is instrument makers. Once we realize the region's historical strength in instrument making, we can better understand Wang's developmental course.

The conventional wisdom is that Wang began the high-tech boom in Lowell. This is true. However, a closer look at the sources of Wang's competitive advantage reveals a link to the region's past that has not been acknowledged. A company engineer captures it.

"One aspect of Wang Labs' experience that gave them a 'one-up' on their competitors is that the company already had experience with real-time control systems. In the early 1960s, before Wang got into the calculator business and well before the computer business, Wang Labs was involved with Warner-Swasey, a company that made metal working machinery such as lathes and milling machines. Wang developed control systems that would automate the operation of these formerly man-operated machines, allowing faster, more accurate machining of precision metal parts. The work of developing these Numerical Control (or "NC," as the technology came to be known) systems contributed to Wang's later development of control systems based on its calculators."[10]

Therefore, before Wang there were instrument makers. If we look at today's surviving technology companies founded before Wang what do we find? We find a sizeable group of highly specialized, testing and instrument makers.

Instrument Makers: Testing and Measuring

GenRad. 1915. 1200 employees. Previously known as The General Radio Company was itself a spin-off of a company established in 1906 to manufacture X-ray equipment. General Radio was founded to exploit the discovery that high voltage spark coils used to excite the x-ray tubes were popular with radio amateurs, or hams, for their transmitters. The new company became a supplier to the radio pioneers as it pursued market opportunities in radio, perhaps as fashionable a term at the time as electronics would become a half-century later. General Radio's "synchronous rectifier" supplied the high voltage required for the first radiotelephone trans-Atlantic communication during World War One. GenRad's long history is rich in instrument innovation but directly influenced by the optical firm of Carl Zeiss, GenRad was decades ahead of its time in introducing participatory models of work organization (Sinclair 1965).

GenRad's Lowell plant, which produces test and inspection equipment for printed circuit board makers, was acquired by Terradyne Inc. (itself founded in 1960) in 2001. The merged company has over 125 years experience in test and measurement instruments and equipment. Teradyne makes automatic test equipment for semiconductor

[10] Rick Bensene, Wang Laboratories: From Custom Systems to Computers," October 2001, updated June 2002, **www.oldcalculatormuseum.com/d-wangcustom.htm.**

manufacturers and packagers; it has been a leader in automated optical inspection technology.

McPherson. 1953. 50 employees. McPherson supplies the world's science labs with optics tools or precision measuring instruments. Its spectrometers measure electromagnetic radiation and enable scientists to investigate small wavelength regions of the electromagnetic spectrum. McPherson instruments vary from miniature to versions that weigh over 20 tons and span 70 feet. The Company's spectrographs (an apparatus for photographing or otherwise recording spectra) fly in space rockets and allow scientists to record and search out ancient events in the universe. McPherson's first product was a spectrometer for Air Force Cambridge Research Lab that was launched into space with an "Aerobe" rocket in 1954.

Thermo Electron has acquired 3 inspection, measurement, and test-equipment operating units in the Lowell area. The Thermo Electron business model combines the advantages of large size with those of decentralization; it is one of a variety of "focus and network" alternatives to both vertical integration and market coordination.

Thermo Electron/KeyTek. Founded in 1975 as Keytek Instrument Corp; became a subsidiary of Thermo Electron in 1994. 90 employees. Manufactures test equipment to measure for electrostatic discharge, power surge, and power quality.

Thermo Moisture Systems Inc. 1976. 150 employees (est.). Became a subsidiary of Thermo Electron in 1996. Manufactures gauges, some of which are microprocessor based, to measure near-infrared reflectance, moisture, and thickness.

Thermo Detection. Founded in 1991 as Thermedics Detection, Inc. 75 employees (230 at its peak). Acquired by Thermo Electron in 1997 (it appears?). Company manufactures detection and inspection equipment including X-ray inspection systems and equipment for narcotics detection, chromatography detection, and bomb detection.

ESA, Inc. (Environmental Science Associates). 1970. 86 employees. ESA designs and builds liquid electrochemical detection equipment for chromatography used in life science testing. ESA's first project was to develop a technique to measure lead in blood; today ESA works on detectors for Huntington's, Parkinson's, and Alzheimer's diseases based on neurochemistry expertise.[11]

HITEC Corporation. 1970. 50 employees. HITEC is an operating unit of First Technology PLC, United Kingdom. It provides mechanical engineering stress consulting and custom strain gauge design engineering and installation services.

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[11] Chromatography, a chemistry-based discipline, involves the separation of a mixture by passing it in solution or suspension through a medium in which the components move at different rates; separations are displayed as a number of colored bands or spots.

Instrument Makers: Photonics and Imaging

The Lowell area has a group of photonics, imaging, and optics companies that could also be classified as instrument makers. McPherson works in optics and GenRad, as noted, was deeply influenced by the organizational innovations of Carl Zeiss, perhaps the world's most famous optical company, formed by Carl Zeiss, a skilled machinist, in 1846. In Massachusetts, the development of related capabilities goes back to the early days of precision machining and age of amateur astronomers.[12]

Barr Associates. 1971. 350 employees. Design and manufacture infrared optical filters from less than 200 nanometers wavelength out to the far infrared (to 35 microns); few companies exist that can meet the challenge of optical filters to these wavelengths.

The latest Hubble Servicing Mission involved the replacement of the Faint Objects Camera with a new, faster, and more powerful Advanced Camera for Surveys. This new piece of equipment is ten times more sensitive, has a wider field of view, and is four times faster at retrieving data. This new instrument contains approximately 25 optical filters designed and manufactured by Barr Associates Inc. (founded by Edgar E. Barr, a pioneer in the production of optical filters during the 1950s).

Dielectric Sciences Inc. 1970. 35 employees. While classified as SUB (subassemblies) its primary business focus is high voltage cable used in X-ray and other imaging equipment.

Space Optics Research Labs. 1962. 20 employees. Parent is McPherson, Inc. Manufactures optical components and systems including laser and optical equipment, and provider of optical manufacturing services to government and aerospace.

Valley Design Corp. 1975. 50 employees. Manufacturer of wafer substrates and provider of photonics manufacturing services including lapping, polishing, dicing, cutting, edge polishing, and grinding. Markets include microelectronics, optical, and semiconductor industries.

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[12] Other interesting optics companies (in terms of history or attractiveness to foreign investors) still operating include American Optical Lens Company formed in 1832 which today has 40 employees and is located in Southbridge, Mass.; The O. C. White Co., a manufacturer of microscopes founded in 1894, with 10-24 employees today, located in Three Rivers, Mass.; Dolan-Jenner Industries, Inc. founded in 1962; currently employs 120 in nearby Lawrence, Mass. Dolan-Jenner makes optical inspection equipment, gauging systems, and fiber-optic illumination systems for multiple industries. Its parent is the Danaher group, which includes Kollmorgen Electrical Optical. More on the early links between skill machinists and the early optical industry in Massachusetts can be found in Michael Best, *The New Competitive Advantage* (Oxford, U.K., 2001), 136. Foreign investment in photonics is considerable in Massachusetts. Of 55 photonics companies in Massachusetts with sales of over $5 million, we have identified operating units with headquarters in the following countries: Germany (5), Japan, Holland (2), Italy, United Kingdom (2), Canada, France, and Switzerland.

Schafer Corp. 1972. 44 employees. Operating unit of a large national defense industry prime contractor. Provides defense industry technology consultants. This unit conducts R&D on lasers and optics (*Mass High Tech* directory).
Optelic US, Inc. 1985. 70 employees. Manufactures video magnification systems and hand magnifiers.
Diamond USA, Inc. 1990. 150 employees. Manufactures fiber optic systems, backplanes, devices, and cable assemblies for telecommunications, astronomy, and engineering businesses.
Cynosure, Inc. 1991. 150 employees. Develops and manufactures medical lasers/optics.

Factory Automation

A third regional technology capability is in automation equipment design and production. Companies in this trajectory include:
Brooks Automation. 1978. 2500 employees. Brooks Automation, which moved to Lowell from nearby North Billerica in 1995, specializes in factory automation equipment for semiconductor manufacturers. This includes flexible manufacturing systems, materials handling equipment, elevators, monorails, storage retrieval systems, three dimension vision systems, robots including grips, arms, wafer handling, transfer equipment, and environmental systems for controlling air quality, humidity and temperature. It is a public company with units in Arizona, California, and Utah. Brooks Automation is an active member of the BASE Council, a consortium of Boston area companies that supply the semiconductor industry
PRI Automation, Inc., Tool Automation Systems Division. 1996. 800 employees in 2000. This unit was acquired by Brooks Automation in 2002 and moved from nearby Billerica to Chelmsford. PRI manufactures robotic interface equipment.
Innovative Products and Equipment, Inc. 1980. 45 employees. Makes custom automation equipment and provides product development services. The Company's website states: "Mission is to guide customers through thicket of technological, manufacturing and testing issues that confront even the most carefully researched new products when they come out of lab and enter mass production." New product development services, in this case, can include process integration of the following activities: "...the creation of initial concepts...design engineering, electrical and control engineering, fabrication, assembly, debugging, installation, training and service." The Company specializes in pharmaceuticals and medical disposables market, which often involves the plastics industry.
Styletek, Inc. 1970. 25 employees. Makes molds for plastic, computer cable and footwear industries. Styletek does not have the technology integration capabilities of factory automation companies such as Brooks Automation. Its inclusion signals the presence in the region of a large group of high precision plastics companies that have developed a

competitive advantage by integrating information technologies with traditional capabilities in machining and tooling.

Microwave Integrated Circuit technology

The Lowell area is also home to a range of microwave integrated circuit making companies, including M/A COM, the region's biggest employer. As the technology that lies behind the growth of Raytheon (the radar segment of the electromagnetic spectrum), microwave technology has a long history in Massachusetts. The leading companies began as defense contractors but migrated to subassembly and components for telecommunications.

M/A COM. 1958. 3300 employees in 2002. M/A comes from *Microwave Associates* began life in 1950 providing magnetrons to U.S. Army Signal Corps. In 1978, its name was changed to M/A COM reflecting a move into wireless telecommunications.

Hittite Microwave Corp. 1985. 150 employees. Hittite designs and manufactures analog/digital integrated circuits in five markets: broadband, cellular, microwave/millimeter, fiber optic, military, and space. Hittite's website lists hundreds of publications in microwave journals.

Microsemi Microwave Products. This was unit founded in 1985. 70 employees. The Lowell plant specializes in "packaging and advanced IC architectures for handling everything from ultra low to high power and from low frequency to ultra high frequency…" (PKA-Silicon Transistor, acquired by Microsemi, a $200 million public company headquartered in Irvine, California that specializes in power management.[13]

Electronic Manufacturing Services

The rapid growth of "contract manufacturing" in Silicon Valley and Asian electronics regions was an early indicator of the shift from the vertically integrated to the vertically specialized business model in electronics. Not surprisingly, in the Massachusetts context of limited consumer electronics production, contract manufacturing did not undergo a similar expansion. The process of vertical disintegration and increased specialization in Massachusetts took a different route. It combined the region's low volume, mixed product industrial heritage with software engineering

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[13] In August 2001, Microsemi acquired New England Semiconductor, which had earlier acquired Silicon Transistor of Lowell. Microsemi also acquired Compensated Devices, Inc. of Massachusetts in August 2001 and, along with Microsemi's Watertown, Mass. operation, and consolidated both in a newly outfitted facility in Lawrence, near its Lowell unit which manufacturers "'high reliability microwave devices and modules." **http://www.microsemi.com/finance/presentations/AnnualReport2002.pdf**.

services to foster "electronics manufacturing services" (EMS) and, increasingly, "electronic design automation" (EDA). EDA involves the extension of computer-aided design (CAD) to concurrent engineering (the integration of product and process design) for rapid new product development.

Today, Massachusetts is strong in EDA (electronic design automation) and software engineering services. Globally, the contract manufacturing sector has morphed into "electronic manufacturing services" as the volume manufacturers have upgraded their capabilities to supply not only high volume components but design services as well. However, leadership in EDA has attracted more traditional production specialists to Massachusetts in search of more advanced new product development capabilities.

The strength of the region in electronic design automation has been obscured by the artificial dichotomy between manufacturing and services in standard industrial classifications systems, a dichotomy that is particularly misleading for understanding product-led competition.

The region's specialization in engineering design services can be traced in part to the demand for systems engineering generated by the Electronics Systems Center (ESC) at nearby Hanscom Air Force Base in Lexington, Massachusetts. The ESC is the U.S. Air Force's site for C^4I, a defense industry acronym that stands for command, control, communications, computers, and intelligence. The ESC has managed nearly 200 C^4I projects going back to the 1950s and the Semiautomatic Ground Environment (SAGE) project, an air defense system involving the integration of technologies underlying missiles, radar networks, gunfire control, guidance systems, and high-speed digital computers.[14] The ESC followed SAGE with management of the Airborne Warning and Control System (AWACS) in the 1970s. Thus, the ESC has been a project manager for an integration of the region's historic capability in complex product systems, such as jet engines and telecommunication switching equipment, with software systems control. The greater Massachusetts region is unmatched in "systems integration" capabilities that cut across computers, communications, and control systems, a heritage that predates Wang Laboratories.

Companies that have contributed to the Lowell area unique capability in electronic design automation include:

Assurance Technology Corporation. 1969. 90 employees. Assurance Technology's specialty is component-testing services with emphasis on space, avionics, and terrestrial military C^4I applications. Their website (**http://www.assurtech.com/**) states that virtually all U.S. satellites are flying Assurance Technology Corporation processed parts.

[14] See Thomas P. Hughes, *Rescuing Prometheus* (New York, 1998), 17.

Dielectric Sciences Inc. 1970. 35 employees. An independent company in both the X-ray/imaging equipment and microwave integrated circuit clusters. Specifically, it makes high-voltage cable assemblies for applications in high-energy physics, military radar, and industrial X-rays. (Dielectric Sciences and Barr Associates develop similar technologies with different applications).

MSL Qualitronics. 1984. 100 employees. Specializes in low-volume and early-stage printed circuit board assembly. Manufacturing Services Limited acquired Qualitronics in 2000 and its name changed to MSL Qualitronics. The parent is located in Concord Massachusetts and has other units in Minnesota and California.

Bull Electronics 1987. 165 employees in 2001. This unit is a division of Groupe Bull, France. It operates in the manufacturing equipment and contract manufacturing space. It appears that it was folded into Bull's 1300 employee Billerica operating unit specializing in computer equipment.

Mack Technologies. 1993. 150 employees. Mack is an electronics manufacturing-services company that recently acquired Sun Microsystems East Coast manufacturing operation including this unit, which specializes on low volume, high complexity products. Its product descriptions include contract computer manufacturing services, design engineering services, double-sided PCB (printed circuit board) assembly services, telecommunication manufacturing services. Each of these product descriptions implies integration of manufacturing and services. The corporate family has four regional operating units Mack Technologies (Westford), Mack Molding (VT), Mack Design (NY), and Mack Prototype (Gardner). Thus, the business model is similar to that of Thermo-Electron.

Wang Years (Lead Companies Established During the Minicomputer Era: 1977-1985)

We now turn to companies that have contributed to the development of regional technological capabilities in roadmaps that were first established during the Massachusetts "Miracle" years. While they built on the region's technology genealogy and industrial heritage, they also involved the establishment of new industrial sub-sectors.

Digital and Image Signal Processing:

Sky Computer. 1980. 100 employees. Image and digital signal processing; builds fast, embedded computers. Sky supplies half the computers for explosive detection systems that scan luggage at U.S. airports. Meets requirements of ruggedness for airborne radar applications. Software compilers and development tools, and software run on multiple systems. While the focus is on industrial imaging, Sky Computer also does medical imaging. Founded in Lowell and acquired by Analogic Corp in 1992.

Mercury Computer Systems, Inc. 1982. 600 employees, 550 in state. Makes digital signal and image processing systems; the Company's embedded computer systems transform streams of sensor data to visual information in real time for analysis and interpretation. Mercury Computer supplies MRI (Magnetic Resonance Imaging) and CT Scan (Computed Tomography) to OEMs (original equipment manufacturer) General Electric, Philips, and Siemens Medical Systems as well as defense contractors. The Company also supplied GCA Corporation's wafer stepper in 1984, a machine used to produce precision-aligned sub micron semiconductor components. Mercury Computer Systems has wholly-owned subsidiaries in the United Kingdom, France, and Japan.[15]

Bard Electrophysiology. 1969. 150 employees. Bard moved to Lowell in 2000. Primary industry is medical; but it also designs and makes specialist computer hardware geared to electrophysiology.

Software Engineering Services: New Product Development

The Lowell area has a dozen or more sizeable software engineering companies that specialize in business services, often design-related services to support rapid and sustained new product development. This capability is closely related to "electronic manufacturing services," which can be interpreted as the convergence of contract manufacturing and information technologies. Included in this section are operating units whose core capability began on the information technology side of the convergence; these companies started with software engineering including circuitry design skills before acquiring hardware side technologies.

Gateway Design Automation Corp. 1982. 331 employees. (Acquired by Cadence in 1991 and name changed to Cadence Design Systems Inc.) Originally, this unit specialized in engineering design services, more specifically in technical/scientific software.[16] Cadence was founded in 1988 in San Jose, California. Cadence, as the name implies, specializes in CAD (computer-aided design) and also in EDA (electronic design automation).

Zuken USA, Inc. 1983. 500 employees. Japanese company established in 1976. Concurrent design tools: Makes CAD/CAM (computer-aided design/computer-aided manufacture) software for multiple brand

[15] Founder James R. Bertelli was with Analogic, a leader in similar imaging processing technologies. Data General provided start-up funds for Mercury. Mercury evolved from producing board level hardware to providing a total system solution: "…product includes a combination of hardware and software…by some of most skilled signal and image processing applications and systems engineers in the industry." The Company's website further states: "…an unmatched degree of expertise in technologies such as radar and sonar signal processing, digital X-ray and computed tomography (CT), and audio and video image compression, decompression, and reconstruction."

[16] SOF-NT Technical/Science software.

workstations and sells to engineering industry. Company offers EDA (electronic design automation) software to improve the integration of design and manufacturing processes in electronics companies.[17] Zuken has PCB design service bureaus in 10 countries and hundreds of "partners."

Quickturn Design Systems, Advanced Simulation Division. 1993. 45 employees. Engineering software (specifically, technical/scientific software). Originally was SpeedSim, Inc.[18] Acquired by Cadence Design Systems and called Cadence Design Foundry. Provides engineering design services for IC (integrated circuit) and expertise that ranges from "System on a Chip" design to analog mixed signal design.

MatrixOne, Inc. 1994. 600 employees. Global product development management. Supplies collaborative PLM (product lifecycle management) solutions. The Company seeks to "provide solutions that unleash the creative power of global value chains to inspire innovations and speed them to market." MatrixOne combined with Tata Consultancy Services (Asia's largest software company) to establish a PLM Center of Excellence to offer Fortune 500 companies worldwide guidance in reducing new product development cycle times. MatrixOne has an office in 11 countries.

Accelerated new product development is not simply a technical exercise; it involves the development of organizational capabilities that extend beyond the boundaries of the firm. In this way the "focus and network" or "open-systems" business model that prevails in the technology producer sectors of post-Massachusetts "Miracle" New England has itself contributed to the development of specialist firms that both practice and diffuse the rapid new product development capabilities of the new model.

Software Engineering Services: Business Development

Kronos. 1977. 2000 employees. Founder's vision was to apply microprocessor technology to automate the employee timekeeping and payroll process. Kronos systems have extended to capture real-time labor data for integration into MRP (material resources planning) and ERP (enterprise resource planning) systems. Rather than compete with business software leaders like Oracle and PeopleSoft, Kronos targets the fragmented middle market.

Kronos original labor time-accounting technology was an electro-magnetic device; in the late 1980s Kronos migrated its product to the PC (personal computer) environment, in the 1990s to LANS (local area networks) and WANS (wide area networks). The idea was that employees did not have to wear badges or punch time clocks as long as they linked indirectly to the company's IT (information technology) system. The

[17] According to Zuken's website, it is the world's first EDA vendor to be listed on level 1 of the Tokyo Stock Exchange.

[18] The firm had the same address as Tality, which is now in San Jose, Calif.

technology has broadened in a second way: to support the "trend toward employee empowerment" including self-monitoring and as the workforce has become more diverse with increasing use of "contractors, part-timers, mobile workers, telecommuters, and home-based workers." While Kronos' product line was primarily in the computer hardware category, it increasingly offers software and services. With the slowdown in IT sales, the market for servicing and upgrading the systems already in place has grown. "In a recessionary environment, we basically sell productivity—the ability for organizations to manage their labor more effectively…."[19] In this way the business cycle shapes product portfolio and the relative shares of manufacturing or services in SIC-based measures of output.

Davox (now Concerto Software, Inc.). 1981. 470 employees; 310 in Massachusetts. Davox began as a supplier of data concentration equipment and computer-voice telephone equipment primarily to call centers. However, this equipment was limited to outbound-based activities. With the acquisition of AnswerSoft, Davox combined outbound- and inbound-based activities enhanced customer interaction features and entered the Customer Relations Management (CRM) market. Now known as Concerto Software, Inc., the Company provides a combined product that embraces telephony, fax, email, and the web to the CRM market.

Thus, Davox began in telecommunications as a supplier of data concentration equipment and telephone voice equipment but moved to facilities management software in 1997. Today Concerto Software sells its CRM product to financial institutions, airlines, TEL providers, insurance companies, utilities, and retailers and has subsidiaries in Canada, United Kingdom, Mexico, Germany, Brazil, Japan, and Singapore.[20]

Iris Associates. 1984. 450 employees. Iris Associates is a Lotus spin-off that makes database file management and office automation software. Referred to as "The haven of Notes and Domino developers." Iris was born when Lotus provided Tim Halvorsen, Len Kawell, and Notes creator Ray Ozzie with the funding to start Iris Associates and develop Notes, in exchange for the exclusive rights to Notes. Lotus purchased Notes in 1988, and Lotus bought Iris Associates in 1994.[21] Iris Associates was independent of IBM (International Business Machines) until integrated into IBM in 2001.

Datawatch Corp. 1985. 80 employees in Massachusetts; 225 total (50 percent foreign sales). Data mining and chart creating software to enhance business productivity.

Digital Voice Systems, Inc. 1988. 20 employees. Voice compression SOF for use in TEL and voice storage applications.

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[19] Investor's Business Daily, 20 Nov. 2001.

[20] Vikor Inc., established in 1992, employed 75 in 2000 in CRM but only 14 in 2003.

[21] Lotus has Westford facilities as well as Iris Associates.

SoftLinx, Inc. (originally Samsung Software). 1993. 40 employees. Provider of Internet and Intranet fax messaging solutions for major corporations and service providers. Offers open-system architecture that enables massive user volume, data communication involving hundreds of thousands of users across vendor platforms and operating systems. SoftLinx is co-located with Lotus's Iris Associates, the developer of Lotus Notes.

SoftLink's title captures partnering role software can play in fostering the 'focus and network' business model: "SoftLinx partners with industry-leading platform and technology companies to offer complete end-to-end solutions that meets our customer's business needs as well as the objectives of our partners." An impressive array of 'Strategic Alliances' as listed on its website. Its alliance with Iris Associates, developer of Lotus Notes, has created market opportunities particularly in Internet fax messaging systems. For example: "IBM [300,000 users worldwide] has selected SoftLinx's Replix ntFAX for Domino and Replix unixFAX or AIX because of its tight integration with Lotus Notes/Domino, mainframe application integration, multi-platform support, flexible architecture, high performance, and excellent customer support."

Mission Critical Linux. 1999. 85 employees. Provides support for application of Linux technologies, the paradigm of open-source systems.

Communication Systems

Communication systems equipment combines the area's strengths in software and telecommunications. Services here involve hardware, in the form of computer terminals, and LAN (local area network) and WAN (wide area network) software. Many of the region's bigger software companies specialized in communications systems, a segment of software before the telecommunications boom of the late 1990s.

NetScout. 1984. 355 employees; 250 in Massachusetts (but only 50 in 1997). NetScout, known until 1997 as Frontier Software Development, Inc., was established as a software company specializing in communications systems. The name change reflects the transition in the Company's technical capability into the area of network traffic monitoring and analysis. NetScout, which works at the interface of networks (LAN and WAN), also provides services in the management of information flow to connect networks and business activities.

Biscom. 1986. 60 employees. Manufactures fax servers (TEL-EM and TD) with communications systems (SOF-CS).

Lincoln & Co. 1978. 10 employees. Lincoln is a unit of Biscom that manufactures printer controllers and related software.

OpenPages Inc. 1990. 50 employees. Supplies B2B (business-to-business) "process automation" services to enable companies to manage content within and across multiple communication channels including web, print, and wireless.

Universal Software Corp. 1992. 140 employees. Corporate family is active in both computer hardware (COM) and telecommunications (TEL). For example, Creative eTECH, Inc. 2000 works from the same location. Whereas Universal focuses on software engineering outsourcing services, Creative eTech provides Internet consulting, development and staffing services. The Chief Executive Officer (CEO) of both is Kishore Deshpande.
Quallaby Corp. 1996. 65 employees. Quallaby develops network performance management software for network service providers.
Brix Networks. 1999. 50 employees. Makes VOIP (voice-over-Internet Protocol gear or network infrastructure and services). Brix Networks is in both the software-communications systems and testing and measurement (TAM-AN) domains. It integrates proprietary network quality monitoring software with testing-and-measurement hardware-appliances. Products are sold to telecommunication carriers and service providers.

Specialty Materials

Finally, specialty materials companies established during the Miracle years are thriving in the Lowell sub-region.
Valley Design Corp. 1975. 50 employees. Innovative techniques in advanced materials processing for "nanotechnology, telecommunications, research, optoelectronics, fiber optics, MEMS." Provides photonics manufacturing services and silicon wafering. Valley Design sells services from "few micron dimension" technologies it has developed and the machines themselves such as dicing, cutting, lapping, and polishing ceramic and silica substrates and optical surfaces. Purchasers of such technologies include Allergan, Johnson and Johnson, M/A COM, Norton Co., and Owens Glass.
Valid Materials Products. 1985. 60 employees. Parent is Ballard Power Systems, headquartered in Canada. Develops and manufactures advanced composites for fuel cell and automotive applications. Company was previously a division of Textron.
Triton Systems Inc. 1992. 75 employees. Specialty polymers, ceramic composites, and metal matrix composites; developer of functional materials including conductive polymers. Triton Systems has several small operating units in the Lowell area including Elecon, Inc. 2001, which conducts R&D in conductive polymer systems (MAT-PO-E, no sales); Sensera, Inc., which specializes in chemical detection equipment (TAM-DE); and Tribond, Inc., a developer of welding equipment (AUT-AS-W).
Konarka Technologies, Inc. 2001. 24 employees. Conducts R&D and makes photovoltaic cells based on light-emitting polymers.

The Post-Wang Years (Lead Companies Established During The 1990s)

Communications Equipment

The post-Wang years have witnessed the establishment in the Lowell area of a high-profile group of data communication companies that provide the network switching equipment for Internet traffic. These companies have been leaders in the design and development of the Internet infrastructure and the associated revolution of the new public network in telecommunications. In fact, a distinctive regional capability has been established in optical network-switching equipment designed to replace [transition from] the conventional telephone backbone with the IP (Internet Protocol) backbone. Leading telecommunications companies such as Siemens, Alcatel, and Nortel were all investors in this group of companies. For the first time, spin offs of new technology enterprises in LCW were being established in surrounding townships.

The Merrimack Valley has historically been a center for voice communication switching and transmission equipment (ex-AT&T (formerly American Telephone and Telegraph)'s Lucent Technology 2 million square foot manufacturing site was located in nearby North Andover). The firms that have developed the regional capability in IP (Internet Protocol) equipment specialize in a range of products and services unified by the integration of hardware and software required to move data, voice, and video over networks. Like the Internet itself, the network-switching equipment suppliers have thrived in an "open-systems" environment with standardized interface rules. Thus while the conventional telecommunications industry was dominated by vertically-integrated companies the new business model is one of focus on core capabilities and networks for complementary capabilities. Consequently, while most of the companies are or have been in the "networks/internet equipment" technology code, each has developed a distinctive core capability that is reflected in different technology product profiles.

Cascade Communications, established in 1990, was the first major Lowell area entrepreneurial firm in the data networking equipment space and fostered a set of cluster dynamic processes. Cascade employed only 28 in 1993 and 134 in 1995 but grew to 400 in 1996 and was acquired by Ascend Communications of California in 1997. However, growth in employment is not what distinguished Cascade Communications; its major role was as an incubator of new firms in IP infrastructure equipment and related services.

Figure 4 captures the spin-off process that is central to the "regional innovation system" that marked the industrial dynamics of the Massachusetts region in the post-Miracle period.[22] Several of the eleven

[22] The term spin-off is used loosely with reference to Figure 4. Simply noting that executives of the new companies had previous employment experience with

firms that spun out of Cascade Communications in the optical-switching equipment sector are located in the Lowell area. The Lowell area has roughly a dozen medium-sized companies with product profiles that include TEL-NW (networking switching equipment) or closely related profiles.

Cascade specialized in providing the "carriers" (companies that provide telecommunication services directly to the public) with new switching technologies for "efficiently directing the congested streams of data flowing across phone lines." The descendants have each specialized in a related but distinctive technology capability.

Integral Access, Inc. 1996. 70 employees. Integral Access provides carriers with the capability to deliver multi-media services (voice, data, video) to small and medium sized businesses and residential customers over copper or fiber-optic links.

Sonus Networks, Inc. 1997. 497 employees. Sonus specializes in voice switches and related design engineering services for IP networks.

Nortel Networks, Ltd., Network Access Division. 1997. 250 employees. The focus of this operating unit is remote access technologies that allow data access efficiently and reliably from distributed locations.

Sycamore Networks. 1998. 400 employees. Sycamore is a direct descendant of Cascade Communications and was founded by the same individual. Its focus is on 'intelligent' optical switching to efficiently aggregate and route network traffic for the Internet backbone. Its "software-centric" switches are classified as fiber optic related equipment under photonics and optics. Like Cascade Communications, Sycamore has fostered numerous spin-offs including Universal Software Corp. and Creative eTECH in the Lowell area and A123, an energy company, in Boston.

Convergent Networks, Inc. 1998. 300 employees. Whereas Sonus focuses on building the backbone of tomorrow, Convergent Networks specializes in integrating backbones of "yesterday, today, and tomorrow to operate seamlessly."

Astral Point Communications. 1998. 180 employees. A Cascade Communications descendant acquired by Alcatel, Astral Point Communications focuses on metro optical systems or edge-routing as distinct from core-routing technologies.

Brix Networks. 1999. 50 employees. (Also profiled under Communication Systems [SOF]). Brix Networks makes "voice-over-Internet Protocol" gear and Internet traffic monitoring services to large enterprises: "From initial assessment, to continuous monitoring, to executive reporting, the Brix System is a multi-faceted...tool that is helping

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Cascade Communications is not enough to qualify as a spin-off in a meaningful sense as executives in many of the new companies had worked for several other companies.

large enterprises…to manage all the phases associated with the deployment of advanced IP services in their networks."[23]

SnowShore Networks, Inc. 2000. 45 employees. SnowShore Networks makes LAN (local area network) servers and hubs and a multimedia processing engine to power a variety of multimedia services including video.

WaterCove Networks, Inc. 2000. 110 employees. WaterCove Networks specializes in wireless phone infrastructure equipment that enables carriers to migrate to third generation (video streaming) without replacing legacy network equipment.

Storigen Systems, Inc. 2000. 65 employees. Storigen Systems specializes in distributed data storage, a critical field in data communications. It offers open-systems storage technology for connecting distributed organizations. Its product profiles include R&D activities in both Internet infrastructure hardware and software.

Narad Networks. 2000. 150 employees. Company specializes in local area broadband IP infrastructure R&D. Based on high-speed Ethernet switching, Narad technology creates cost-efficient, fiber-like performance over existing HFC (hybrid fiber coax) networks.

Mintera Corp. 2000. 43 employees. A photonics R&D company specializing in optical transport solutions for long distances (10,000 Km) at high volume and speed (40 Gbit/sec). It seeks to be the "…technology leader in 40G (40 gigabyte) transport solutions for metro-core, regional, long-haul and ultra long-haul optical networks."[24]

Environmental Engineering Services and Equipment

ENSR International (originally Environmental Research and Technology, Inc.) 1968 (moved headquarters from Acton Massachusetts. in 2000). 1267 employees in 70 worldwide locations. Consulting and engineering services including engineering design services for world's largest air quality measurement systems; hazardous waste treatment plants; co-generation power projects; environmental control systems for refineries, chemical manufacturing facilities, and pulp mills; and process re-engineering for waste minimization. Operates aquatic toxicity and hydraulic design laboratories. ENSR was a subsidiary of the German headquartered RWE Ag and NuKEM GmbH during the mid-1990s.

Ionpure Technologies, 1989; now USFilter/Water and Wastewater Group, a subsidiary of Vivendi Universal. 200 employees. Ionpure Technologies manufactures a range of water purification equipment.

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[23] Frank Tutalo, "Brix Gets Insurance Giant as Customer" *Lowell Sun*, 12 March 2003.

[24] See **www.mintera.com/news_media.html.**

Environmental Science Associates (ESA, Inc.) 1970. 86 employees. ESA is in the testing and measurement and medical technology sectors. It designs and applies electrochemical detectors for high performance liquid chromatography.

General Observations

What follows are a set of observations derived from our historical analysis of the Lowell-Chelmsford-Westford townships.

1. In contrast to conventional economic histories of regions in which the long-term trend is one of industrial decline in traditional industries punctuated by short-lived shocks, such as Wang, our story focuses on the region as having a history of technological continuity and change. We see the region and the Lowell area as home to a critical mass of specialized technology producers.

These contrasting visions illustrate the idea that what an observer sees is highly dependent upon the classification system used. The technology classification system we used reveals that the Lowell area lacks manufacturing companies in the sense of enterprises that crank out widgets. That the New England region has few high volume manufacturers is underscored by the fact that only 56 of 4692 companies in the *Mass High Tech Directory* of companies are in the "consumer electronics" category.

2. The companies located in the Lowell area today represent continuity of capability development with the surrounding region's technological heritage in instruments and equipment-making long before the Massachusetts "miracle." These firms are part of a larger historical dynamic in which a region's competitive advantage is established by the cumulative and collective development of specialist technological capabilities.

This history is captured in the leadership the region has played in driving down critical size dimensions as shown in **Figure 1**. Continuity in driving down critical size dimension lies behind the leadership Massachusetts has enjoyed in the introduction of next generation technologies.

3. Dividing the founding of Lowell area companies into 3 periods illustrates three related themes. First, the regeneration of the Lowell area in the 1970s benefited from the technological dynamism of greater Boston and the regional capabilities in instruments and complex equipment linked to the region's historic achievements in inquiry and analysis. The building of Route 128 followed by Interstate 495 established a transportation infrastructure that made the region attractive for companies seeking to relocate for purposes of space and property expenses.

In the pre-Wang and Wang periods technology producers founded elsewhere moved to the Lowell area. The post-Wang period was the first time since the textile period that Lowell area companies founded new technology companies and sub-sectors within the region. For example, data communication equipment companies were both founded and located in the Lowell area.

Changing product portfolios illustrate that most, if not all, survivors have new product development capability. Their survival depends upon integrating production and a range of business services required in the new product development process. Thus the CorpTech technology classification not only offers the degree of specificity required to capture technological distinction, by offering information on product portfolios, it also indirectly reveals enterprises that integrate manufacturing and services while SIC codes are anchored in their separation.

4. The Lowell area is part of a global technology community in specialized instruments and equipment. As shown in **Chart 4**, a quarter of the Lowell area companies export 25 percent or more of their product. **Table 2** shows that 15 operating units in the Lowell area are or have been owned by parent companies with foreign headquarters. This illustrates the theme that the Lowell area technological capabilities are better known within the global technological communities than locally.[25]

5. Unlike the American Midwest, New England has never been a leader in economies of speed or in application of the principle of flow to manufacturing. Instead, the region specializes in production capabilities related to low-volume, high-mix processes. Since the establishment along the Connecticut River Valley in western Massachusetts of the first machine-tool industry (at least the first machine-tool industry based on the principle of interchangeability), the region has advanced production capabilities in machine and tool making, an antecedent and complement to instrument and equipment manufacturing.[26]

The fundamental principle of production around which the region's industrial leadership was organized in the nineteenth century was the principle of interchangeability. Here, too, we find a long historical process of cumulative and collective capability development. High volume production activities migrated to other regions organized according to the principles of flow and mass batch production. The different historical trajectories are captured in **Figure 2**. Not surprisingly, the production system that prevails in the operating units of Lowell area technology producers is one of low-volume, high-mix output.[27]

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[25] Many Silicon Valley companies have acquired operating units in the Lowell area to benefit from the region's unique, specialized capabilities. Examples include Sun, CADENCE, and Cisco Systems.

[26] European "machine tool" industries were embedded in the craft tradition; hence, the technology trajectory was not one of driving down critical size dimensions, a precondition to mass production.

[27] If the success of high volume production is the principle of flow, the secret to the success of technology product production is the principle of systems integration.

6. The business model that prevails in the Lowell area can be described as focus and network. The idea is to focus on core capabilities and partner or network for complementary capabilities. **Figure 3** contrasts the focus and network business model with the vertically integrated business model for the PC industry. It is a post-Chandlerian, visible hand world that fosters the decentralization and diffusion of design across networked groups of specialist enterprises.

The focus and network business model is, in part, a consequence of the new product development imperative for technology producers. Here again the standard industrial classification codes obscure dynamic processes. In contrast to the loss of manufacturing as a process of de-industrialization, we find greater interdependence between manufacturing and service activities and the transformation of both in an age of rapid new product development. The linkages between production and business services are an important way of driving down new product development cycle times.

7. Dynamic industrial districts can be explained in terms in the principle of systems integration. Systems integration is a principle of organization, which refers to the capacity of a system to reconfigure itself to take full advantage of design improvements in sub-systems. Systems integration, from the dynamic capabilities perspective, is critical to the success of industrial districts, low, medium, or high tech. Some have pointed to the rapidity in which firms in industrial districts can move from reorganize over fashion seasons by sharing orders. Systems integration is different; it is a process of mutual development of complementary capabilities and is made possible by open-systems.

8. The focus and network business model is associated with high rates of new firm creation (see **Figure 4**) and high rates of industry "churn" (see **Table 3**). High rates of churn in turn foster rapid redeployment of resources and regional capability development. The fast growing firms and the new entrants in Table 3 absorb resources released from the exiting firms. The same process lies behind the rapid growth of telecommunications shown in **Table 4**. In this case, resources released from computer hardware and computer software enabled rapid growth in telecommunications, which absorbed those resources.

9. In many cases, the new firms are spin-offs. The spin-off process is implicit in the focus-and-network business model: technologically-advancing firms generate more potential development opportunities than they can pursue without losing focus. **Figure 4** shows a burst of spin-offs from Cascade Communications in the data communications switching gear industry. Spin-offs are part of a techno-diversification process that enhances the region's innovation.

10. Technology-driven companies have fostered a new, collaborative model technology management in response to the challenge for rapid new product development. Rapid new product development is the "heart and soul" of technology driven companies. Yet, the capacity to

invest in product development is limited and the yield is highly variable. The response to this challenge has been the development of a new model of technology management based on networking to leverage each participating company's core capabilities. Technology management in the vertically-integrated business enterprise began with the development of functional departments for new product and process development. The functional approach to new product development was replaced by a process integration approach supported by focused, cross-functional project teams. The next organizational step was the idea of portfolio competition in which strategic business units were increasingly organized in terms of technology strategies. The new model is one of inter-firm collaboration to leverage core capabilities of product development partners.

11. The new business model fosters participation in technology alliances. An example is the BASE (Boston Area Semiconductor Equipment) Council, an association of companies including Brooks Automation of Lowell that supply equipment to the semiconductor industry (see **Figure 5**.)[28] The member companies operate in the same technology domain, but specialize in complementary capabilities. This allows members to share strategic concerns about and, if possible to shape, the technology roadmap of the semiconductor industry.

A second example of a technology alliance supported by a Lowell area company, Teradyne, is the National Electronics Manufacturing Initiative (NEMI). NEMI "provides an environment in which partners and competitors alike can collectively anticipate future technology and business needs and effectively develop collaborative courses of action to meet those needs."[29]

These are examples of technology alliances or networks that conform to the logic of the focus-and-network or open-systems business model and the need to anticipate market opportunities by shaping a technology roadmap. They are different from traditional trade associations, which seek to lobby government on behalf of the membership.

12. High-tech industrial districts, like all industrial districts, depend upon the development of "networking" institutions to coordinate groups of specialist enterprises. Networks, in effect, "thicken" markets relative to vertically-integrated enterprises and thereby reduce barriers to entry.

The Internet is an example of a networking institution. Besides reducing barriers to entry, it is a great enabler of design integration to serve rapid new product development along the supply chain.

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[28] BASE started as a cooperative effort in training and TQM (total quality management).

[29] **http://nemi.org/about/index.html**.

Thus networking institutions are vehicles for facilitating specialization by enhancing opportunities for firms to focus on core capabilities without the need to invest in complementary capabilities.

13. The Lowell city government was not responsible for creating the high-tech industries in the region. However, it was responsive to the opportunities and created an environment that attracted new enterprises and fostered their growth and associated "cluster dynamics."

The Lowell city government established industrial parks in the 1970s.[30] As in cities everywhere, these parks were largely unsuccessful until 1977. That was the year that Wang relocated to Lowell. In the meantime, the city government leveraged national and state resources to create the country's first national urban park, and under the leadership of Senator Paul E. Tsongas, a Lowellian, invested in numerous civic institutions including the baseball park, the arena, and the summer festivals. Lowell turned its industrial heritage into an asset, and then did something more important. It transformed itself from a city with a history of immigrants into a modern city genuinely proud of its diversity. These investments created a living environment that is attractive to high-tech workers; when companies come to the Lowell area, they stay.

14. What role has University of Massachusetts-Lowell played? One role is captured in **Figure 6**. The key to sustaining growth has been increasing the supply of skilled people in sync with the demands of growing firms and industries. The output of engineers and science majors nearly doubled from 600 to 1200 per year during the Wang years. This was expensive, but highly trained individuals are a condition for sustained growth in output based on new product development and high-tech industries.

15. Captured by "cluster dynamics" that drive dynamic tech capabilities at regional level, including speciation. Exemplified by biotech and "tools" companies in region.

The range of instrument and toolmakers in the region illustrates Adam Smith's "law" of increasing specialization. Massachusetts has a unique collection of specialist "tools" companies.[31] Here Adam Smith meets Edith Penrose. The unique collection of specialist tool companies lies behind the region's leadership in the creation of new industrial sectors and sub-sectors. This is illustrated by the rapid development of the biotech industry in the Cambridge area.

In the words of Jim Vincent (chair and CEO of Biogen Inc.) and Henri Termeer (chair and CEO of Genzyme Corp.): "...many of the tools revolutionizing the pharmaceutical discovery and development process—genomics, bioinformatics, and combinatorial chemistry—have been

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[30] Ross Gittell, *Renewing Cities* (Princeton, N.J., 1992).

[31] "Tools" companies can be found in each of the 7 commercial market sector categories in Massachusetts. Examples include Genomics Collaborative, Phylos, Surface Logix, Alkermes, Millennium, and ArQule.

invented and *continue to flourish in this region*." (italics added). They continue: "it is no wonder that a number of the world's major pharmaceutical companies have chosen to locate research and development facilities in the Boston area."[32]

Inter-firm Networking and the Geography of Systems Integration

Two forms of inter-firm networking offer an alternative to either vertical integration or market coordination (make or buy) of complementary capabilities in a production system. The first is closed-system networking as exemplified by the Japanese *keiretsu*. The closed-system networking model fostered the principle of multi-product flow and the associated leap in performance standards (cheaper, better, faster) that underlay the New Competition of the 1970s and 1980s.

The second type is open-systems networking as exemplified by the PC industry. Open-systems networking is also referred to as horizontal integration, multi-enterprise integration, inter-firm cooperation, networking, loose coupling, or affiliated groups of specialist enterprises. Specialist companies within a regional system of enterprises can integrate, disintegrate, and re-integrate with other companies as technologies and market opportunities change.[33] This is the domain of systems integration and reintegration.[34]

The competitive advantage that systems integration enables is based on the sustained refinement of capabilities offered by a dynamic between capability development internal to the firm and the composite capability of a system or critical mass of capability-networked enterprises. Thus, the existence of an open-systems PC industry enables individual firms to pursue highly specialized capability development and network for the complementary capabilities. The resulting decentralization and diffusion of design enhances capability specialization, capability development and innovation potential of the system of enterprises.

The organizational advantage of an open-system industrial district is that the pursuit of diverse technological capabilities and market opportunities by business enterprises involves endless reconfigurations of enterprise networks and capabilities. The reconfiguration of networks is the means by which clusters are redesigned to capture the "full advantage"

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[32] Vincent and Termeer, "New England's Important Role in the Biomedical Revolution," *Boston Globe*, 25 March 2000, A15.

[33] This process of combining, constituting, and reconstituting offers an explanation of high value-added regions such as Singapore and Hong Kong associated with integration and packaging capabilities Michael Enright, David Dodwell, and Edith Scott, *The Hong Kong Advantage* (Hong Kong, 2000).

[34] Such serial partnering is unique to open-system networks.

offered by technological advances in elements within the cluster. At its best, it is a self-assembling or self-organizing mode of regulation.

The "churn" of enterprises in an industrial open-system is an enabler of Schumpeterian creative destruction that, in turn, facilitates technological change and industrial transition.[35] Churn enhances the capacity of a regional system of enterprises to reconfigure in response to the inherent fallibility of even brilliant innovators to predict the technological future, on the one hand, and the inherent uncertainly of technological change, on the other. The dilemma is captured by Paul Severino, a serial entrepreneur in Boston's Route 128 region: "Ken Olsen [founder of DEC] was and is brilliant but one man can not always guess right about the future."[36]

Network reconfigurations are reinforced by spontaneous regroupings of skills across enterprises in an open-system.[37] New product development can involve inter-firm, virtual technology teams or "communities of practice."[38] Regional economies that have the capability to rapidly reconfigure networks of enterprises and to spontaneously regroup skills to take advantage of innovations in sub-systems can be said to have systems integration and reintegration capabilities. Such a region, if not all of the firms within it, is an infrastructure for rapid new product development involving multiple technologies.

The potential for network reconfigurations and spontaneous regroupings of technology teams depends upon an open-system model of industrial organization and cross-firm project teams. However, the existence of "open-systems" not only fosters reconfigurations and regroupings, it creates an industrial infrastructure that acts back on capability specialization within and among the constituent enterprises.

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[35] This churn of enterprises counteracts the "innovator's dilemma" of single companies as described by Clayton Christensen in *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (Boston, Mass., 1997), but only if the region is populated by the "open-system" or focus and network business model. Regional technology capabilities are secure if the regional system of enterprises includes both incumbents and attackers. In contrast, a region in which free entry is limited risks blocking the entry of firms with disruptive technologies much like the Upas tree poisons the seedlings of other species of plants around it; for an example of heavy engineering killing of alternative technologies and regional growth in Glasgow, Scotland, see S. G. Checkland, *The Upas Tree: Glasgow 1875-1975: A Study in Growth and Contraction* (Glasgow, 1981).

[36] Comment made at the Senior Executive Forum, University of Massachusetts Lowell, 25 March 2002.

[37] Annalee Saxenian, *Regional Advantage: Culture and Competition in Silicon Valley and Route 128* (Boston, Mass., 1994).

[38] John Brown, and Paul Duguid, "Mysteries of the Region: Knowledge Dynamics in Silicon Valley," in *The Silicon Valley Edge: A Habitat for Innovation and Entrepreneurship*, ed. Chong-Moon Lee (Stanford, Calif., 2000), 16-39.

This specialization, in turn, fosters technological innovation and the potential for yet more new enterprises and new configurations of enterprises.

CHART 1

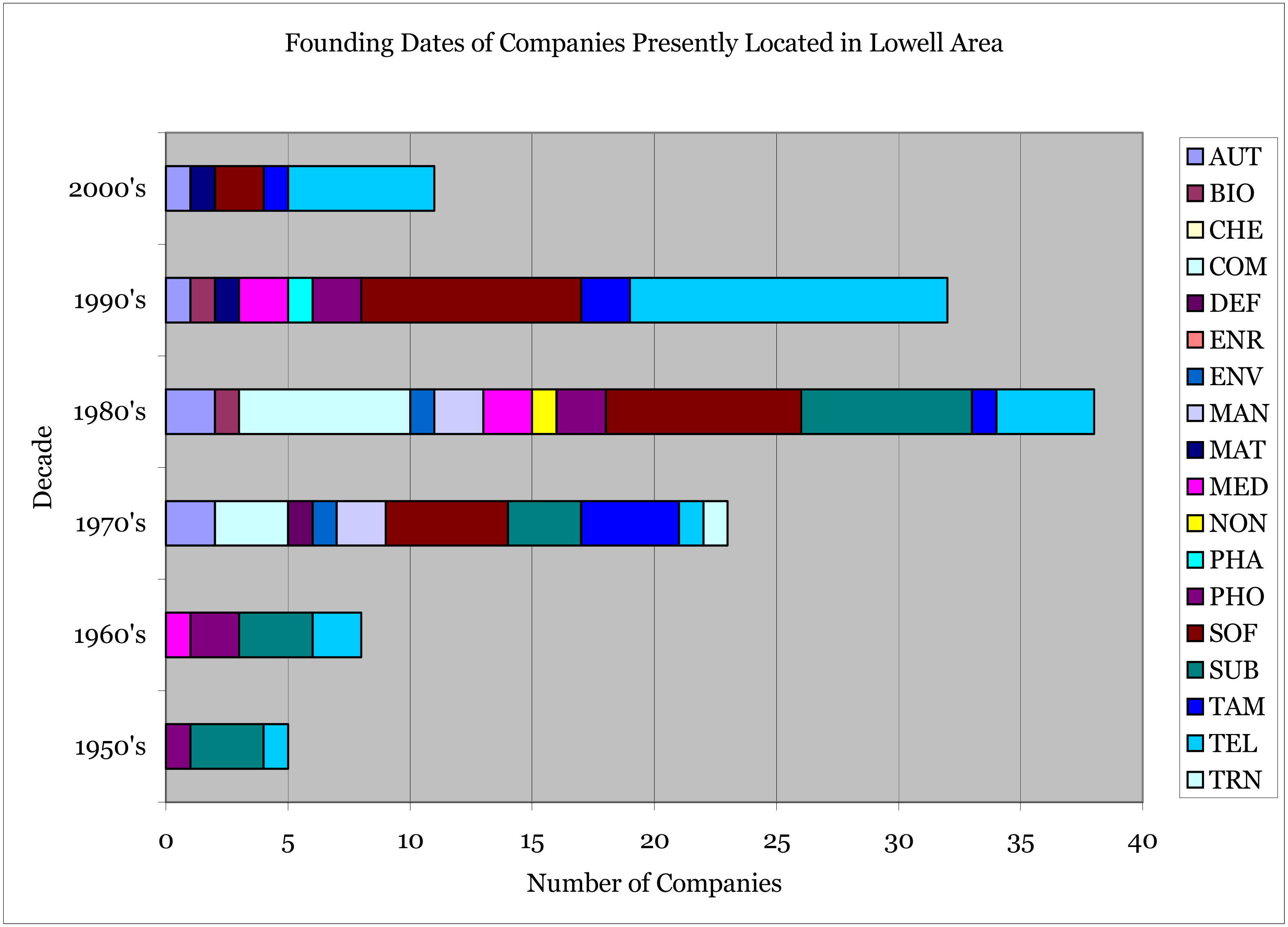

Founding Dates of Companies Presently Located in Lowell Area
Decade
2000's
1990's
1980's
1970's
1960's
1950's
0
5
10
15
20
25
30
35
40
Number of Companies
AUT
BIO
CHE
COM
DEF
ENR
ENV
MAN
MAT
MED
NON
PHA
PHO
SOF
SUB
TAM
TEL
TRN

CHART 2

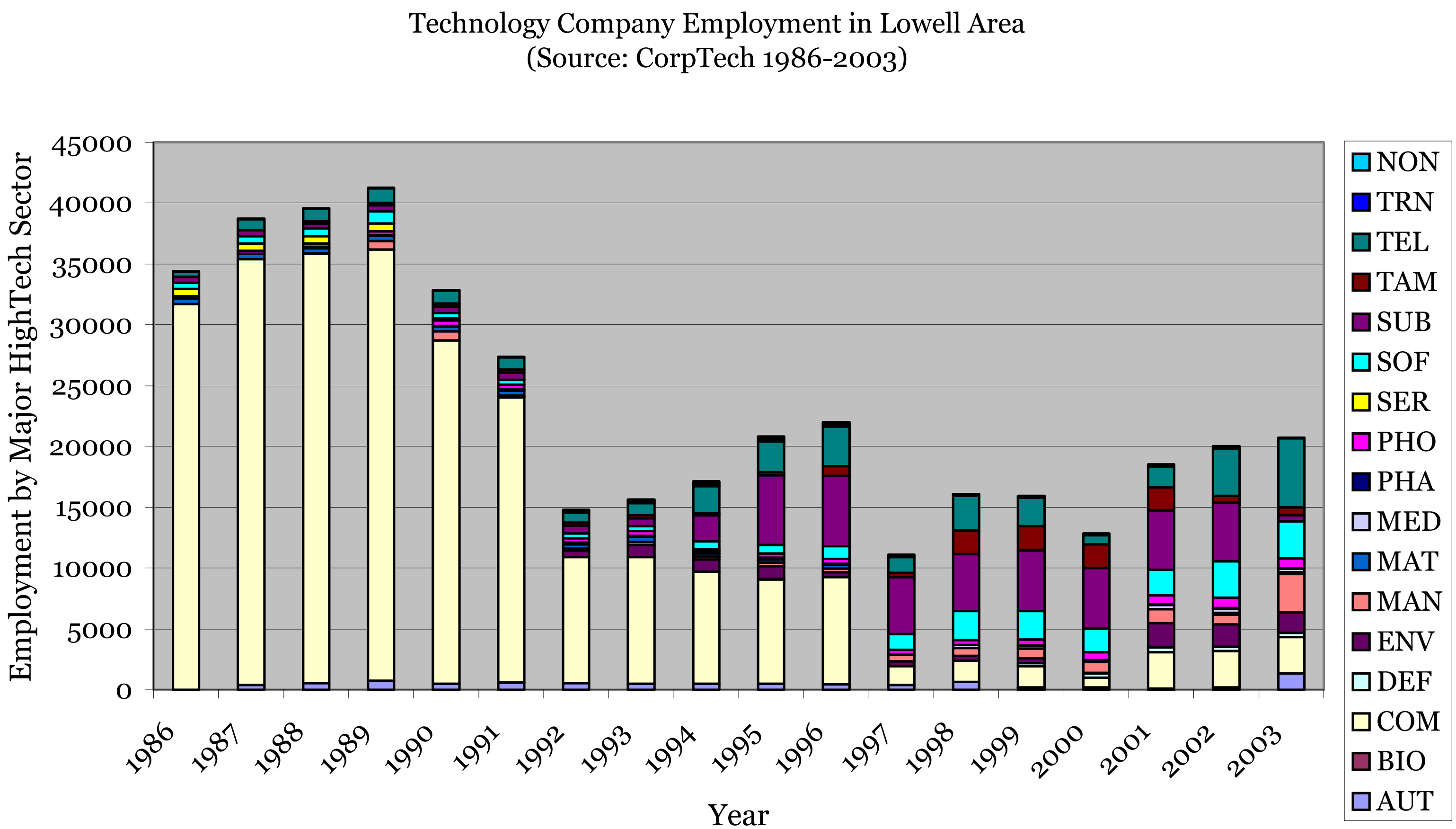

Technology Company Employment in Lowell Area
(Source: CorpTech 1986-2003)
Employment by Major HighTech Sector
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
Year
NON
TRN
TEL
TAM
SUB
SOF
SER
PHO
PHA
MED
MAT
MAN
ENV
DEF
COM
BIO
AUT

CHART 3

Technology Company Employment in Lowell Area (exclude COM)
(Source: CorpTech 1986-2003)

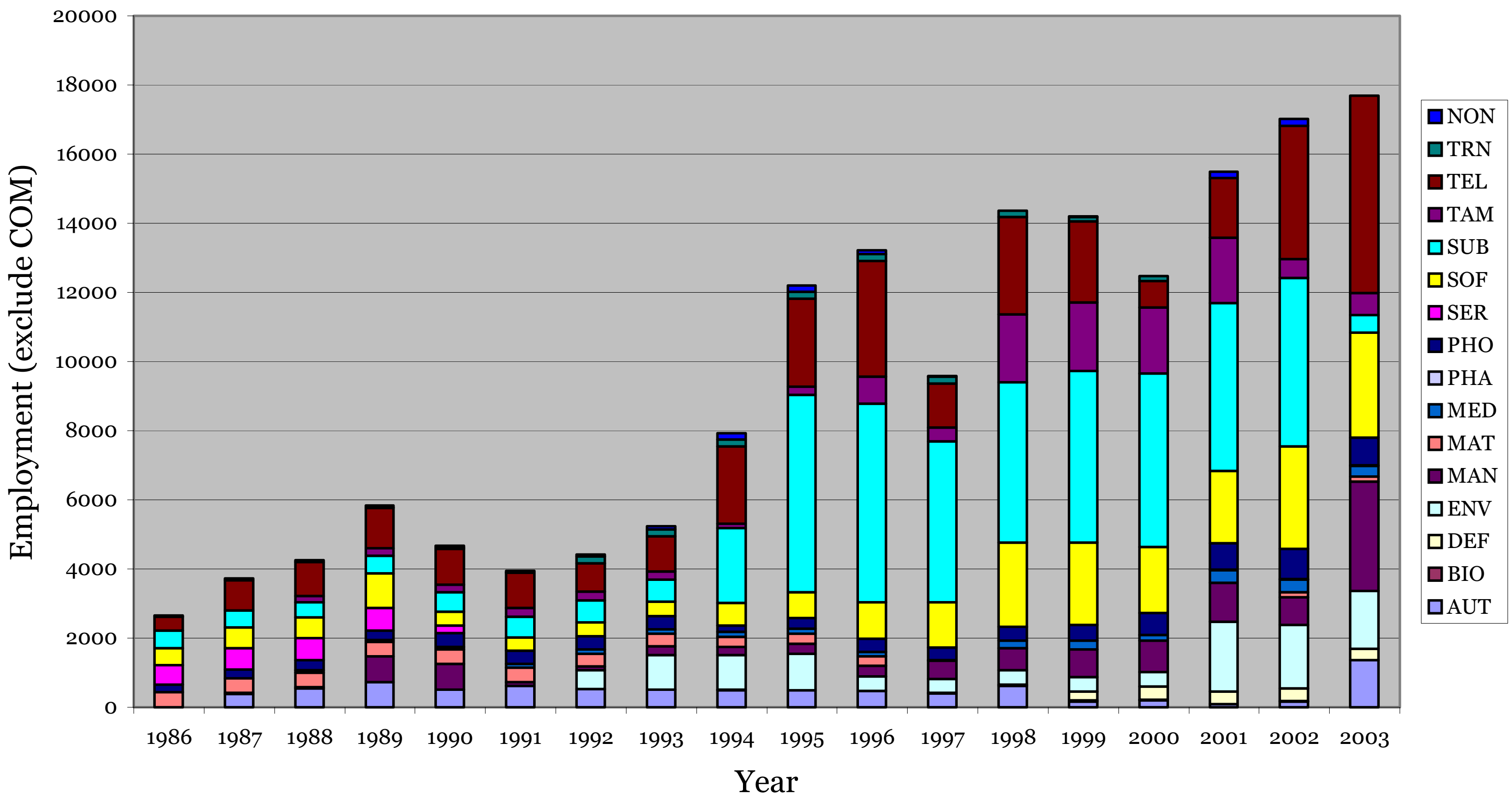


CHART 4 Company Statistics in Lowell Area

% Foreign Sales	
# of Foreign Sales	24
<2.5%	10
2.5-10%	8
10-25%	19
>25%	20
% Unknown	19
Total	100
Declined Info.	*6*

Sales (USD)	
<$2.5 Million	16
$2.5 to 5 Million	16
$5 to 10 Million	11
$10 to 25 Million	16
$25 to 50 Million	4
$50 to 100 Million	6
$100 to 250 Million	4
$250 to 500 Million	2
>$500 Million	0
Declined Info.	*12*

Total Employees	
<10	17
10-24	30
25-49	15
50-99	18
100-249	13
250-499	9
500-999	4
1000-2499	3
2500-4999	2
>5000	0
Declined Info.	*5*

Total Companies	
Lowell	33
Chelmsford	51
Westford	39

TABLE 1

Regional Dynamic Capabilities in the Lowell Area

	Founded	Emp.	Own	Foreign Sales (% of T)	Foreign Sales (M)	Govt.	Previous Town	Moved to Area
Pre-Miracle Years								
Microwave IC Technology								
M/A COM	1958	3300	DO	u	u	u	Waltham, Mass.	
Hittite Microwave Corp.	1985	150	P	10-25%	$8.25	P/S	Woburn, Mass.	2000
Microsemi Microwave Products	1985	70						
Instruments								
Teradyne Assembly Test Division (FKA GenRad)	1915	1200	DO	u	u	u		
McPherson	1953	50	P	10-25%	$.75-$1.88	P/S		
(Assurance Technology Corporation)	1969							
Thermo Electron								
– Thermo Electron/KeyTek	1975	90	DO	>25%	$3.50	u		
– Thermo Moisture Systems, Inc.	1976	150	DO	>25%	$0.55	u		
– Thermo Detection	1991	75	DO	2.5%- 10%	$.24-$1.2	u		
ESA Inc.	1970	86	P	>25%	$0.17	P/S	Bedford, Mass.	
HITEC Corporation	1970	50	F	<2.5%	$0.16	u		
Factory Automation								
Brooks Automation	1978	2500	D	>25%	$72.96	u	North Billerica, Mass.	1995
Innovative Products and Equipment, Inc.	1980	45	P	10-25%	$.50-$1.25	u		
Styletek, Inc.	1970	25	P	2.5-10%	$.0625-$.25	u		

	Founded	Emp.	Own	Foreign Sales (% of T)	Foreign Sales (M)	Govt.	Previous Town	Moved to Area
Photonics and Imaging								
(McPherson)	1953							
Barr Associates	1971	350	P	10-25%	$3.3-$8.25	P/S		
Dielectric Sciences Inc.	1970	35	P	10-25%	$.5-$1.25	P/S		
Space Optics Research Labs	1962	20	DP	10-25%	$.75-$1.875	P/S		
Schafer Corp.	1972	44	P	u	u	u		
(Axis Communications, Inc.)	1984							
Optelec US, Inc.	1985	70	P	u	u	S	Harvard, Mass.	
Cynosure, Inc.	1991	150	P	u	u	u	Bedford, Mass.	1997
Diamond USA Inc.	1990	150	P	u	u	u	Littleton, Mass.	1998
(Mintera Corp.)	2000	43						
(Konarka Technologies, Inc.)	2001							
Electronics Manufacturing Services								
Assurance Technology Corporation	1969	90	DO	none	none	P/S		
(Dielectric Sciences)	1970							
(Schafer Corp.)	1972							
MSL Qualitronics	1984	100	DO	u	u	u		
Bull Electronics	1987	165	F					
Mack Technologies	1993	150	P	u	u	u	Marlborough, Mass.	1999

	Founded	Emp.	Own	Foreign Sales (% of T)	Foreign Sales (M)	Govt.	Previous Town	Moved to Area
Miracle Years								
Digital and Image Signal Processing								
Sky Computer	1980	100	DO	10-25%	$1.7-$4.25	S		
Mercury Computer Systems, Inc.	1982	600	D	10-25%	$15-$37.25	P/S		
Bertelli	1998							
Bard Electrophysiology	1969	150	DO	>25%	$6.25	u	Haverhill, Mass.	1997
Software Engineering Svs. for Bus. and Prod. Dev.								
Kronos	1977	2000	D	none	none	u	Waltham, Mass.	2000
Concerto Software (FKA Davox)	1981	470	D	10-25%	$9.4-$23.5			
Vikor Inc.	1992	14						
Cadence (FKA Gateway Design Automation Corp.)	1982	331	D	>25%	$357.50	u		
Zuken USA, Inc.	1983	500	F	u	u	u	Burlington, Mass.	2000
Iris Associates	1984	450						
Datawatch Corp.	1985	225	D	>25%	$4.50	u	Wilmington, Mass.	1999
Digital Voice Systems	1988	20	P	>25%	$0.75	u	Burlington, Mass.	
Quickturn Design Systems (Advanced Simulation Division)	1993	45	DO	10-25%	$0.058-$1.45	u		
SoftLinx, Inc. (FKA Samsung Software)	1993	40	P	>25%	$1.25	u	Chelmsford, Mass.	2000
MatrixOne, Inc.	1994	600	D	u	u	u	Chelmsford, Mass.	2002

Mission Critical Linux	1999	85	P	<2.5%	$0.03	u		
Communications Systems Hybrids								
NetScout	1984	55	D	u	u	u	Tewksbury, Mass.	1995
Axis Communications, Inc.	1984	23	F	>25%	$0.98	u	Woburn, Mass.	1999
Quallaby Corp.	1996	65	D	u	u	u	Paris, France	
Biscom	1986	60	P	2.5-10%	$.225-$.9	S	Billerica, MA	1993
OpenPages, Inc.	1990	50	P	u	u	u		
Universal Software Corp.	1992	140	P	u	u	u		
Creative eTECH, Inc.	2000	140	DP	u	u	u		

	Founded	Emp.	Own	Foreign Sales (% of T)	Foreign Sales (M)	Govt.	Previous Town	Moved to Area
Captivate Networks	1997	93	P	u	u	u		
Brix Networks	1999	40	P	2.5-10%	$.0375-$.15		Billerica, Mass.	2000
Specialty Materials								
Valley Design Corp.	1975	50	P	10-25%	$.5-$1.25	S		
Valid Materials Products	1985	450						
Triton Systems, Inc.	1992	75	P	u	u	S	Marlborough, Mass.	

	Founded	Emp.	Own	Foreign Sales (% of T)	Foreign Sales (M)	Govt.	Previous Town	Moved to Area
Resurgence Years: Internet Era 1990s								
Data Communication and Networking Equipment								
Cascade Communications Corp.	1990	922						
Integral Access, Inc.	1996	70	P	u	u	u		
Astral Point Communications, Inc.	1998	180	F	u	u	u		
Sonus Networks, Inc.	1997	497	D	10-25%	$17.3-$43.25	u		
Nortel Networks, Ltd. (Network Access Division)	1997	250	F	u	u	u		
Sycamore Networks	1998	400	D	u	u	u		
Convergent Networks, Inc.	1998	300	P	u	u	u		
SnowShore Networks, Inc.	2000	45	P	>25%	$0.25	u		
Wireless Communication Systems								
Brix Networks	1999	50-99	P	2.5-10%	$.0375-$.15	u	Billerica, Mass.	2001
WaterCove Networks, Inc.	2000	110	P	none	none	u		
Airvana, Inc.								
Environmental Engineering Services and Equipment								
ENSR International (FKA Environmental Res. & Tech., Inc.)	1968	1267	P	10-25%	$16.7-$41.75	P/S	Acton, Mass.	2000
USFilter/Water and Wastewater (FKA Ionpure Technologies)	1989	200	F	u	u	u		
Environmental Science Associates (ESA, Inc)	1970	86	P	>25%	$1.68	P/S	Bedford, Mass.	

Emerging Technologies

Storigen Systems, Inc.	2000	65	P	none	$0.00	u
Narad Networks	2000	125	P	none	$0.00	u
Mintera Corp.	2000	43	P	none	$0.00	u
Konarka Technologies, Inc.	2001	24	P	u	u	u

TABLE 2

Foreign Companies with Operating Units in the Lowell Area

Company	Year Founded	Parent	Parent Country
Astral Point Communications, Inc.	1998	Alcatel	France
Flextronics International/Product Introduction Cer	1988	Flextronics International, LTD	Singapore
HITEC Corporation	1970	First Technology PLC	UK
Hyperwave Information Management, Inc.	1997	Hyperwave, AG	Germany
SOPRA, Inc.	1990	SOPRA SA	France
USFilter/ Water and Wastewater Group	1989	Veolia Environnement	France
Zuken USA, Inc.	1983	Zuken, Ltd.	Japan
SoftLinx	1993	Samsung	Korea
Axis Communications	1984	Axis AB	Sweden
ENSR International	1968	Rhein-Westphalian Electric Company	German
ElTech Electronics	1984	ElTech Electronics LTD	Singapore
Ferrotec America Corp.	1989	Ferrotec, Japan	Japan
Discom	1971	TDK	Japan
Bull Electronics	1987	Groupe Bull	France
Nortel Networks, Ltd. (Network Access Division)	1997	Nortel	Canada

TABLE 3

Software Industry Churn

Entry and Exit: SOF firms in Lowell, Chelmsford and Westford (1997-2003)

Company Name	Year Formed	Base year 1997	1998	1999	2000	2001	2002	2003
Frontier Software Development, Inc.	1984	50						
Carberry Technology	1989	10						
Electronic Book Technologies, Inc. / Carberry	1989	10						
Voicetek Corporation	1981	120	175					
Statistics Unlimited, Inc.	1986	5	5					
Connolly International, Ltd.	1991	25	25					
Gartner Group Learning	1987	N/A	66					
ProMetrics Software, Inc.	1982	10	85	10				
Adra Systems, Inc.	1983	180	190	65				
Gulf Computer, Inc. / LangBox Division	1994	200	200	100-249				
Gulf Computer, Inc.	1979	200	200	200			Exit	
Gulf Computer, Inc. / Spartacus Technologies	1981	200	200	100-249				
GeoTel Communications Corp.	1993	N/A	115	200				
Mehta Corporation	1991	N/A	85	75				
Spacetec IMC Corporation	1991	N/A	76	76				
Utility Systems, Inc.	1987	11	11	11	11			
Software Solutions of America, Inc.	1979	6	6	6	6			
Quester Software Services, Inc.	1977	3	3	<10	<10			
Silinsh Software	1984	1	1	1	1			
Fundvest, Inc.	1983	N/A	2	2	2			
ONTOS, Inc.	1985	60	60	60	40	40		
EDS-Scicon, Inc.	1984	N/A	N/A	70	100	100		
Quallaby Corp.	1996	N/A	N/A	N/A	N/A	90		
Iris Associates, Inc.	1984	96	160	350	350	350	500	
Harmon Technologies, Inc.	1985	N/A	N/A	10	10	10	10	
Global Telemedix, Inc.	1995	N/A	N/A	N/A	16	16	16	
NextPoint Networks, Inc.	1996	N/A	N/A	N/A	50-99	N/A	300	
e-StudioLive, Inc.	1971	N/A	N/A	N/A	N/A	N/A	50	
American Business Systems, Inc.	1978	16	17	16	17	17	14	14
A.P. Software	1987	1	1	1	1	1	1	1
Visual Solutions, Inc.	1989	10	10	10	10	10	10	10
Crown Systems, Inc.	1980	6	6	6	6	6	6	6
SoftLinx, Inc.	1980	20	30	30	30	30	40	40
Nonprofit Management Systems	1983	3	3	3	3	3	3	3
Lerman Associates	1985	2	2	2	2	2	2	2
Trix Systems, Inc.	1994	23	12	12	13	16	17	17
Davox Corp.	1981	N/A	300	300	300	398	400	470
NetScout Systems, Inc.	1984	N/A	140	190	220	220	364	355
Lincoln & Co.	1978	N/A	N/A	10	10	10	10	10
Quickturn Design Systems, Inc. / Advanced S	1993	N/A	N/A	39	45	45	45	45
MatrixOne, Inc.	1994	N/A	N/A	200	350	366	500	600
Duxbury Systems, Inc.	1976	N/A	N/A	N/A	13	13	13	15
Datawatch Corp.	1985	N/A	N/A	N/A	230	230	175	98
Zuken USA, Inc.	1983	N/A	N/A	N/A	N/A	N/A	500	500
Tariva, Inc.	1991	N/A	N/A	N/A	N/A	N/A	14	14
Digital Voice Systems, Inc.	1988	N/A	N/A	N/A	N/A	N/A	20	20
Asset Technology Group	1991	N/A	N/A	N/A	N/A	N/A	3	3
Universal Software Corp.	1992	N/A	N/A	N/A	N/A	N/A	140	140
Viridien Technologies, Inc.	1997	N/A	N/A	N/A	N/A	N/A	60	Exit
Hyperwave Information Management, Inc.	1997	N/A	N/A	N/A	N/A	16	N/A	N/A
Vikor, Inc.	1999			N/A	N/A	N/A	45	14
Brix Networks	1999			N/A	N/A	N/A	N/A	66
EnrichNet, Inc.	1999			N/A	N/A	10	10	Exit
Provanum Co.	1999	Entry		N/A	N/A	3	3	
Financial Systems Architects	1999			N/A	N/A	14	14	10
Mission Critical Linux, Inc.	1999			N/A	N/A	75	75	8
IBEX Process Technology, Inc.	2000				N/A	N/A	9	18
Amperion, Inc.	2000				N/A	N/A	1	Exit

TABLE 4

Telecommunications Industry Churn

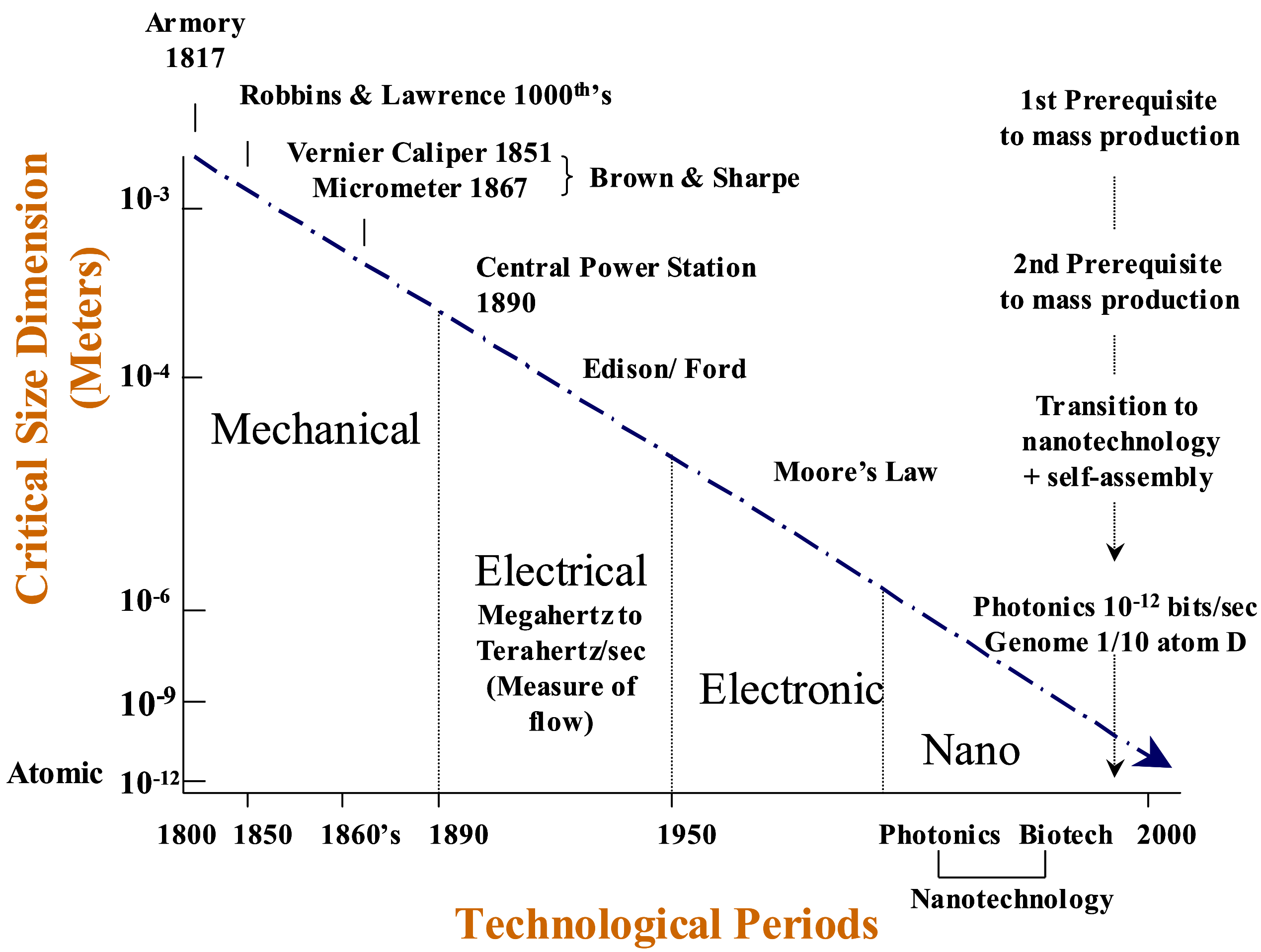
Dynamics Within Telecommunications Cluster 1999-2001
Telecommunications Companies in the Lowell, Chelmsford and Westford Regions

Base Year 1999		2000			2001		
Company Identification	Employees	Company Identification	Employees	Year Formed	Company Identification	Employees	Year Formed
A	150						
B	500						
C	90						
D	53						
E	1						
F	922						
G	80						
H	1						
I	90	I	100				
J	31	J	31				
K	54	K	54				
L	60	L	60				
M	40	M	80				
N	18	N	18		N	19	
O	70	O	60		O	60	
P	25	P	25		P	25	
Q	75	Q	162		Q	250	
Total Companies 17	Total Employees 2260	R	18	1971	R	52	1971
		S	55	1984	S	50	1984
		T	115	1997	T	745	1997
		Total Companies 12	Total Employees 778		U	70	1990
					V	15	1991
					W	10	1994
					X	110	1996
					Y	150	1997
					Z	70	1997
					AA	300	1998
					BB	460	1998
					CC	66	1999
					DD	100	1999
					EE	750	1999
					FF	66	1999
					GG	14	1999
					HH	7	2000
					II	14	2000
					JJ	100	2000
					KK	30	2000
					LL	125	2000
					MM	140	2000
					NN	60	2000
					Total Companies 27	Total Employees 3858	

Summary of Yearly Changes

Year 2000		Year 2001	
Company Status	Employment	Company Status	Employment
Companies Lost 8	Job Loss 1797	Companies Lost 5	Job Loss 325
Companies Staying in Telecom 9	Job Expansion from Prior Year 127 Job Carry-Over from Prior Year 463	Companies Staying in Telecom 7	Job Expansion from Prior Year 748 Job Carry-Over from Prior Year 453
Companies Entering Telecom 3	Job Creation in Telecom 188	Companies Entering Telecom 13	Job Creation in Telecom 2181
Newly Formed Companies 0		Newly Formed Companies 7	Job Creation from New Companies 476

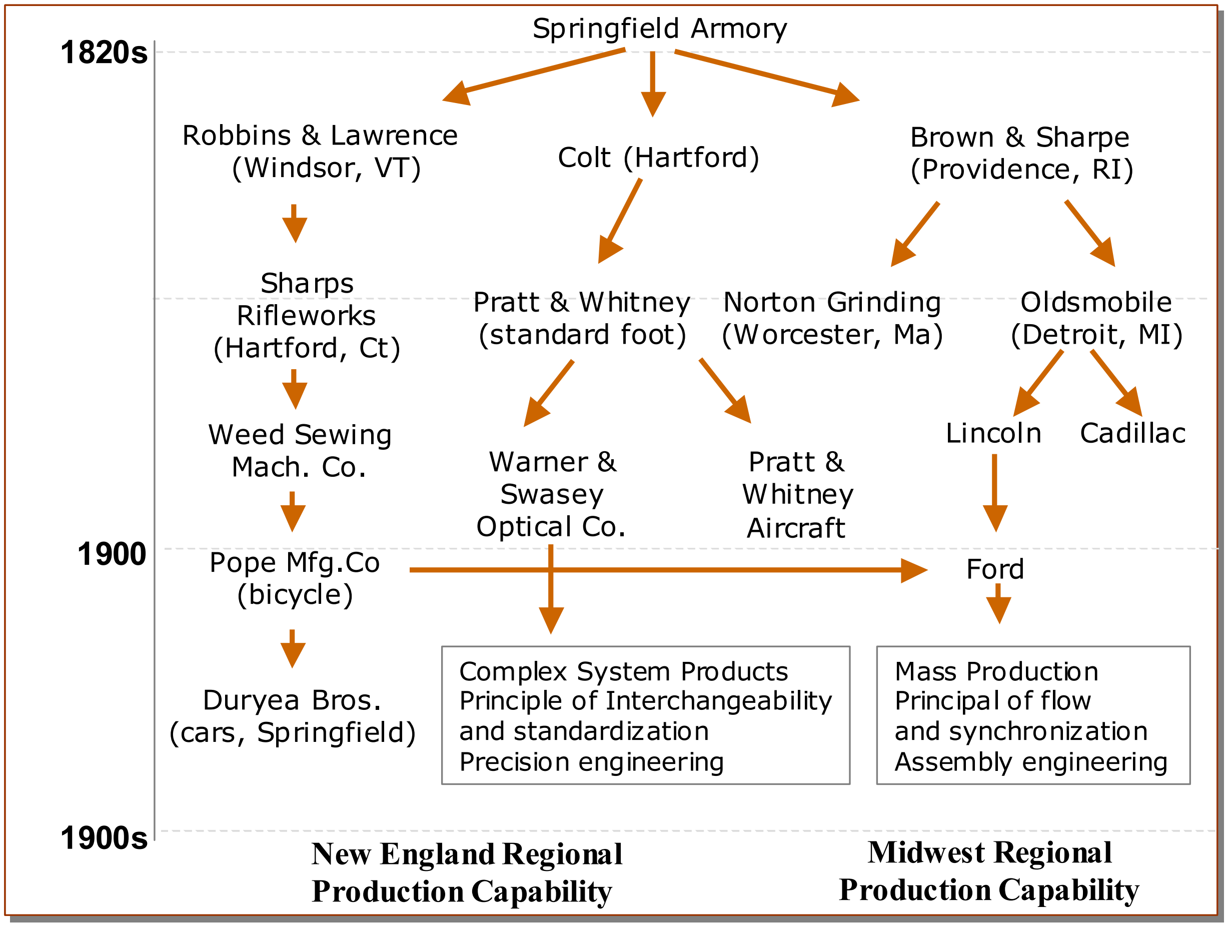
FIGURE 1
Law of Diminishing Sizes



Source: Michael Best, *The New Competitive Advantage*.

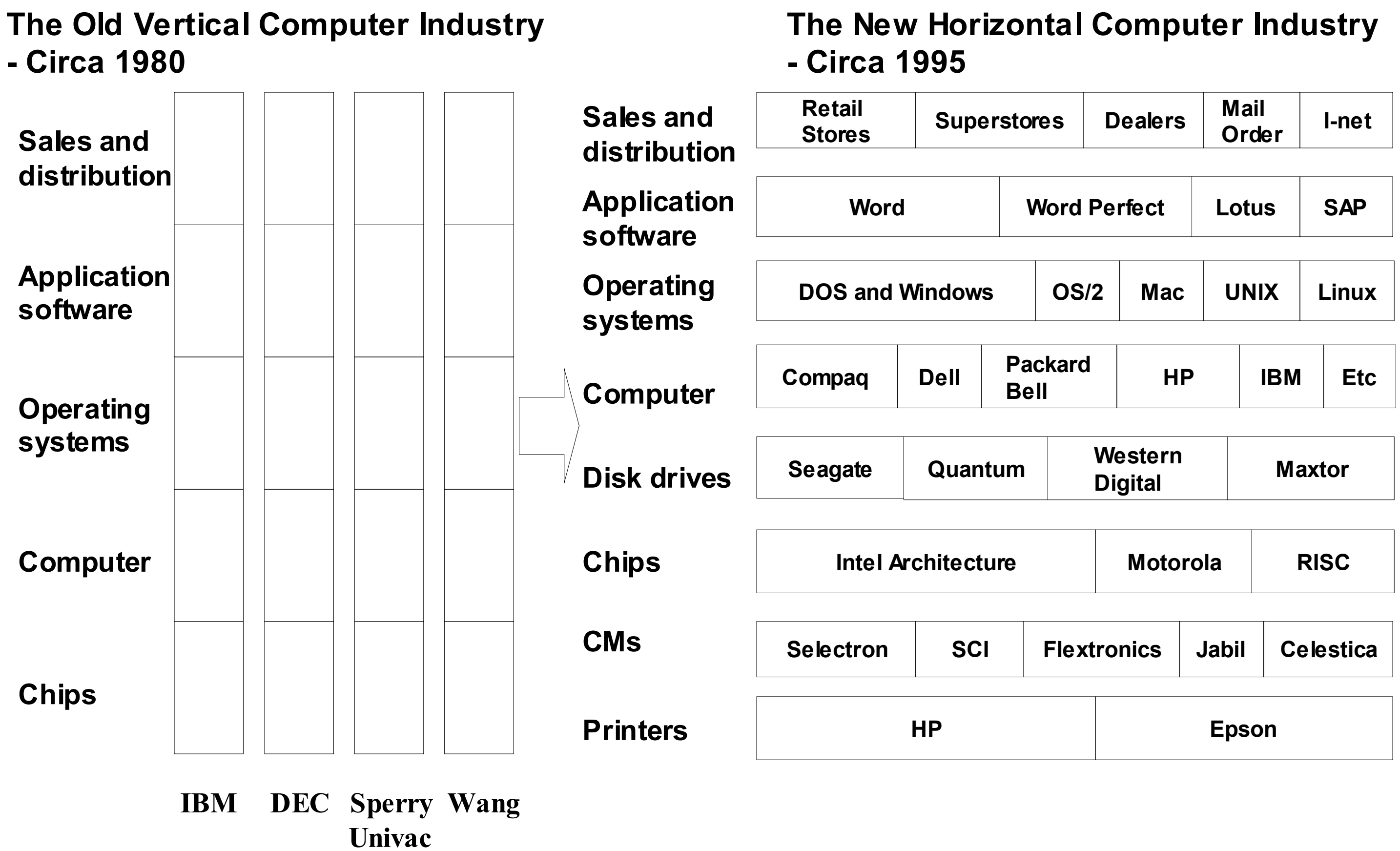
FIGURE 2

Genealogy of Two Regional Production Systems



Source: Michael Best, *The New Competitive Advantage*.

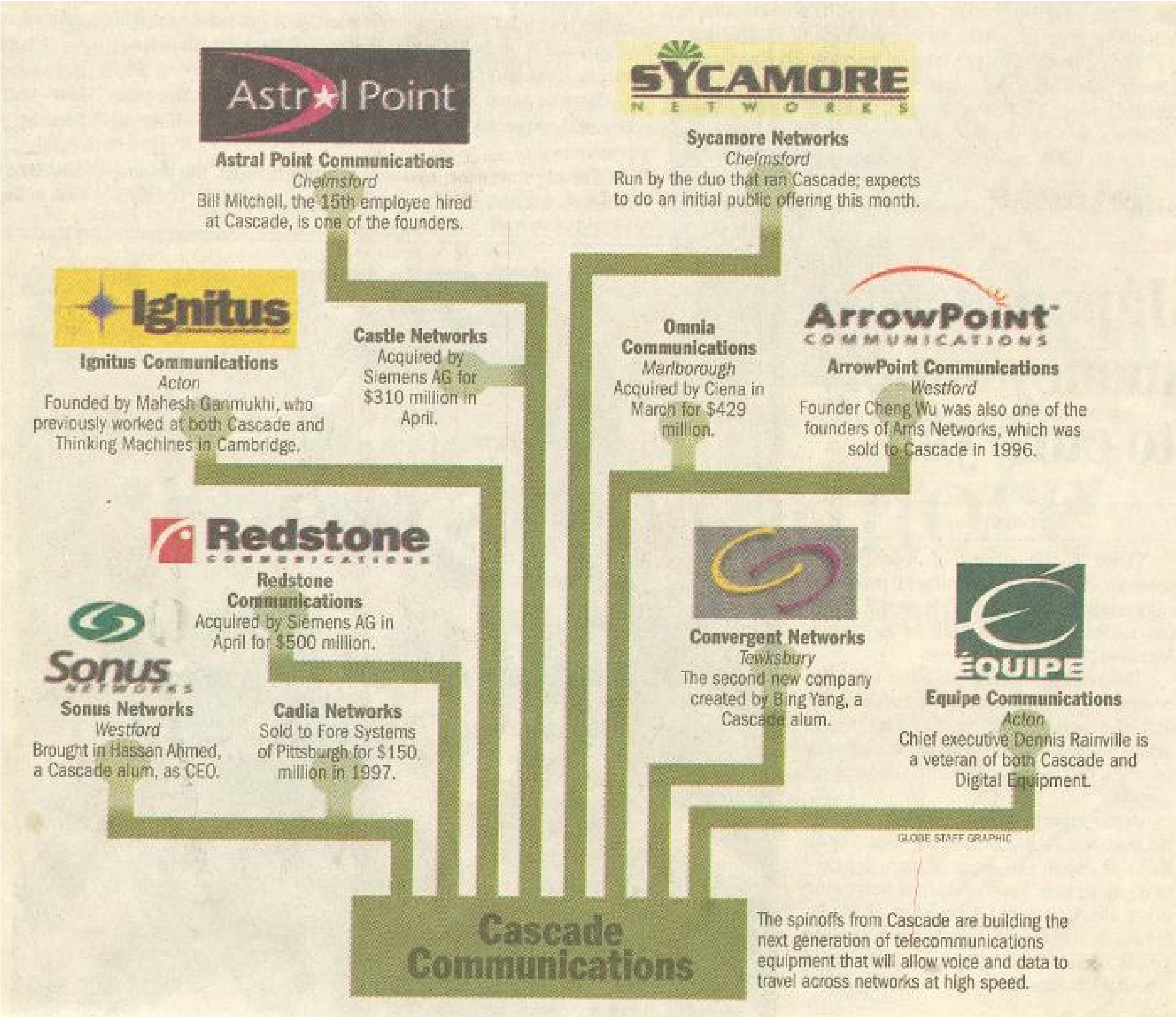
FIGURE 3
Competing Business Models



Source: Adaptation from *Only the Paranoid Survive* by Andrew Grove, 1996.
Used by permission of Doubleday, a division of Random House, Inc.

M. Best, *NCA*

FIGURE 4
Family Tree: Data Communications Equipment



Source: Steven Syre and Charles Stein, *Boston Globe*, 14 Oct. 1999.

FIGURE 5
BASE Council Members

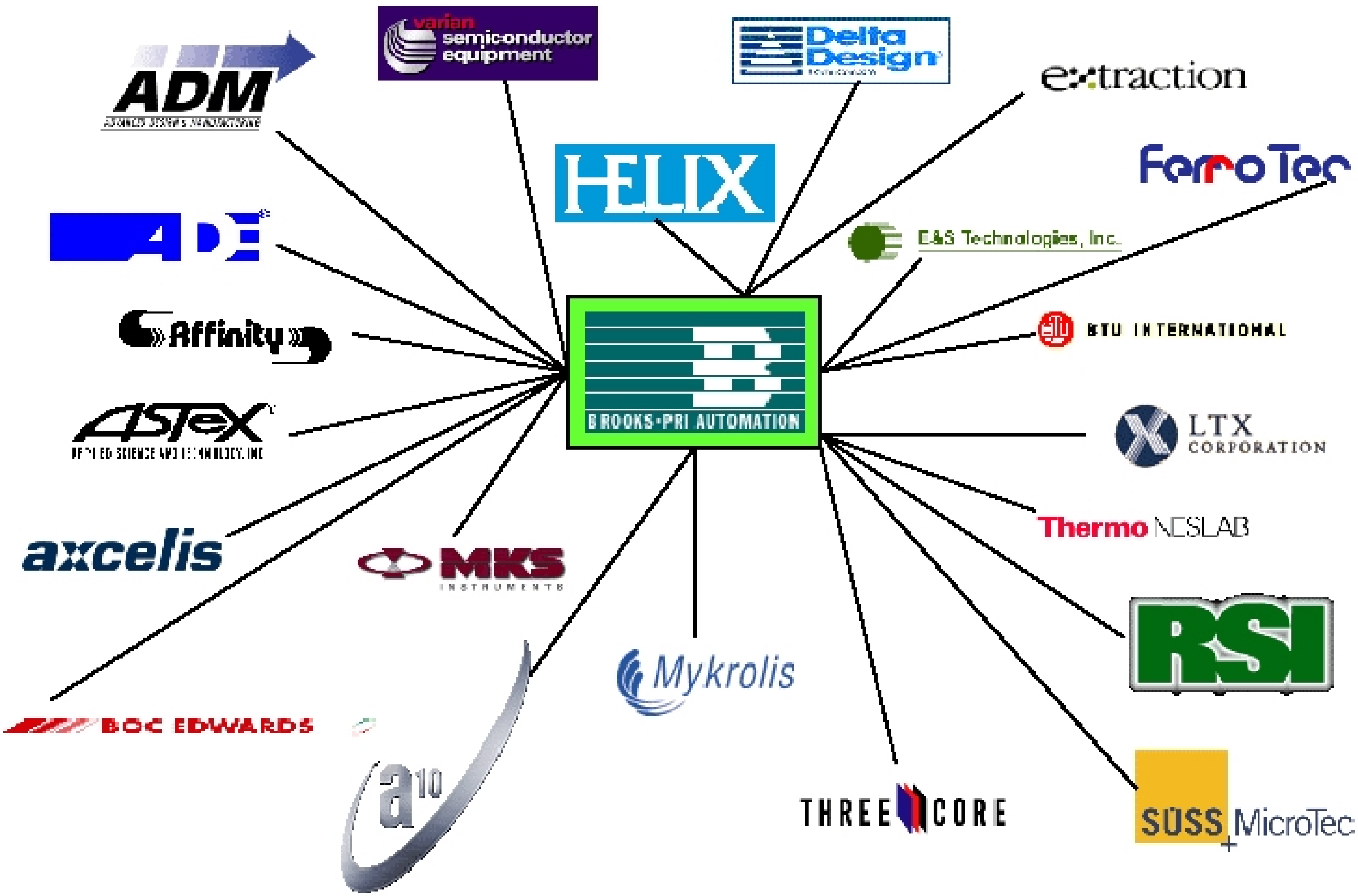


FIGURE 6
University of Massachusetts Lowell Engineering, Math, and Science Degrees 1976-2002