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Regional Capabilities and Industrial Resiliency

Specialization and Diversification Dynamics in Lowell, Massachusetts

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For the pattern is more than the sum of the threads; it has its own symbolic design of which the threads know nothing.   Arthur Koestler

Specialization versus Diversification

Why are some regions more innovative than others? Is innovation fostered by specialization or diversity? Despite decades of debate there is no unequivocal answer to these questions. The so-called Marshall-Arrow-Romer view is that innovation is stimulated by local economic specialization where it is driven by knowledge spillovers among local firms in the same or closely related industries. In the view associated with Jane Jacobs, however, innovation is advanced by local economic diversity and heterogeneity as variety increases the scope for interaction, serendipity and new ideas.

Empirical tests have not settled the matter. Glaeser and colleagues have found support for positive effects on growth for urban industrial diversity (1992). Henderson, in contrast, finds strong support for same-industry concentration on productivity at the county level (1997; 2003).[3]

Michael Porter weighed in on the side of specialization but of clusters of linked industries rather than industries *per se* (2003:562). He critiques macroeconomic debates on growth and policymaking for being conducted at too high a level of aggregation but he argues that industry is too narrow a unit because of "…externalities across related industries

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[3] See Cortright (2006) for a review of empirical studies addressing the specialization versus diversity debate.

within clusters" (2003:562). His concept of cluster cuts across sector lines to include suppliers in other sectors as well as service providers, specialized labor inputs, and demanding customers.[4]

Most empirical contributions to the debate share a common research methodology: specialization is defined and measured in terms of the official SIC (Standard Industry Classification) or the new NAICS (North American Industrial Classification System) codes. Using either industry sector or linked sectors as the unit of analysis and measurement has a major drawback: they do not control for differences in business organization. Dynamics of specialization and diversity that operate at the level of the firm and inter-firm relationships may be too finely grained to be captured at the sector level.

Failure to control for business organization is particularly problematic in regional comparisons.[5] For example, the large performance gap between Silicon Valley and Route 128 in the computer industry can not be traced to differences in specialization measured by employment by SIC or NAICS codes. The SIC sector defined measures obscured the critical difference in business models in the two regions. The Route 128 minicomputer companies were vertically integrated; the Silicon Valley minicomputer and PC companies were vertically specialized into "open-system', focus and network business models (Grove 1996).[6] Thus similar measures for output and employment in the two regions masked paradigm differences in firm organization and inter-firm adjustment processes.

The failure to account for inter-firm specialization dynamics is not a problem for high tech industries alone. The networked groups of vertically specialized small firms that populate the furniture industry of regions in Italy dominated the vertically integrated furniture firms of North London. A regional industry that employed over 16,000 in the 1960s, North London furniture industry employed only 500 by the mid 1980s (Best 1990: 228).

The term networking covers very different forms of inter-firm relations. It can mean simply the commercial business to business relations of specialists along the supply chain. It can involve long-term partnering in complementary capability development across numerous new product generations as in the case of the PC, aircraft (Prencipe 2000), or furniture industries. It can refer to groups of firms cumulatively and jointly advancing distinctive production capabilities, such as precision instruments, or technologies, such as biotech.

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[4] Porter defines clusters briefly as "geographical concentrations of linked industries" and more expansively as follows: "We define a cluster as a geographically proximate group of interconnected companies, suppliers, service providers and associated institutions in a particular field, linked by externalities of various types" (2003: 562).

[5] "Regional comparisons offer a huge, almost untapped source of evidence about how our economy really works" (Krugman 1991: 99).

[6] When DEC, located in Route 128, for example, designed and developed every major component in the minicomputer, numerous specialist companies emerged for every computer component in Silicon Valley.

Pressure to introduce business organization into economic geography is coming from another direction. Advocates of science and technology policy argue that business organization has important implications for industrial innovation (Broers 2005). The corporate practice of owning research labs was based on the presupposition of a one-way relationship from scientific research to technological advance to market leadership. The presupposition collapsed with the emergence of product-led business models organized to compete on the basis of leadership in the introduction of new products. In the new model, basic research became subservient to technological research and both to product development.[7]

The new business model has both organizational and geographical implications. Whereas the default organizational context of the science-push model of innovation was the multi-divisional enterprise, today it has become one of a regional innovation system exemplified by Silicon Valley.

However, despite the changes in the real world, business organization remains a shadowy figure in the major theoretical perspectives on economic geography. This is changing. Porter finds that vigorous domestic business rivalry and the "…creation and persistence of competitive advantage in an industry" are strongly associated empirically (1990: 117). He adds that "…the important influences on…innovation are intensely local" (1990:144) and that "competitive advantage is created and sustained through a highly localized process" (1990:19). The challenge is explicate the specific localized processes that influence innovation and create competitive advantage. Instead, all too often, innovation is conceptualized as an externality, usually in the form of a 'knowledge spillover' across co-located firms.[8]

The exception is evolutionary economic geography in which recent contributions have transcended explanations in terms of externalities and gone inside the firm to account for patterns of spatial agglomeration. It has much in common with the capabilities perspective which informs this paper. Both suggest an interpretation of regional specialization that focuses attention on processes of differentiation and specialization within and amongst firms. We start with a review of the contributions of evolutionary economic geography before turning to the capabilities and innovation perspective of Edith Penrose (1959).

From Routines to Regional Capabilities

In a recent survey Ron Martin (2005: 17) states the following:

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[7] Japanese consumer electronics companies were leaders in integrating technology management into the new product development process and both into a highly flexible production organization. In brief, they extended the principle of flow from single product to multiple product to new product integration (Best 2001: 40-46).

[8] "Clusters are important because of the externalities that connect the constituent industries, such as common technologies, skills, knowledge and purchased inputs" (Porter 2003: 562).

"An evolutionary perspective emphasizes dynamic competitive advantage, and the adaptive capabilities of a regional economy to respond to shifts and changes in markets, the rise of competitors, and the development of new technologies. A region's competitive advantage is the complex outcome of its past development—path dependence—and its capacity to create new pathways of development".

But much research remains to be done. Martin adds: "…we know little about the processes of regional economic adaptation, or about why some regions seem to be more adaptive than others…An evolutionary perspective…would place…emphasis on a region's propensity to innovate, both within and amongst firms, and within and amongst its institutions" (2005: 30).

To address the challenge 'routine', a core concept first developed to explain business success by Nelson and Winter (1982),[9] has been extended to explanations of regional specialization.[10] In the words of Boschma and Frenken (2006: 6): "The emergence of spatial agglomerations is…to be analyzed in terms of historically grown spatial concentration of knowledge residing in organizational routines". The primary organization is the business enterprise and the selection process for routines is organizational competition: [The] "…starting point is to view organizations as competing on the basis of their routines…built up over time" (Boschma and Frenken 2006: 6).

The concept of routine in evolutionary economics serves two functions towards meeting the challenge posed by Martin. The first is to shift the concept of competition from price to organization. Whereas conventional microeconomic theory assumes firms make the same product and compete on price, evolutionary theory holds that firms compete on the basis of differentiated routines. It is a short step from competition over routines to Schumpeter (and Broers) notion of innovation as new product development:

"…as organizations compete on the basis of their routines, competition is driven by Schumpeterian innovation based on new products and technologies requiring new routines rather than on production costs alone as assumed in neoclassical models" (Boschma and Frenkenl 2006: 6).

The second function of routine, exemplified by the term 'organizational' skills, is ontological, to do with the assumed constitution of economic reality. Production in real companies and economies has irreducible collective and interactive dimensions that are obscured by theories which assume production can be decomposed into independent 'factors of production'. The skills term in 'organizational skills' points to accumulated learning effects and tacit knowledge embedded in production processes which influence organizational productivity and competitiveness.

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[9] Nelson and Winter conceptualized the organization "…as a set of interdependent operational and administrative routines, which slowly evolve on the basis of performance feedbacks" and routines as "stable patterns of behavior that characterize organizational reactions to variegated, internal or external stimuli" (Zollo and Winter 2002: 7).

[10] The challenges for evolutionary economic geography are to understand the "spatial distribution of routines over time", the "creation and diffusion of new routines in space" and the "mechanisms through which the diffusion of 'fitter' routines occurs" (Boschma and Frenken 2006: 6).

However, the introduction of routine is less successful in explaining regional specialization. It is not because of lack of effort and it is not without promise. Boschma and Frenken develop the concept ‘related variety’ to distinguish amongst sectors that are closely related from those that are truly diverse: related variety is defined as ‘complementary capabilities among sectors’ (Boschma and Frenken 2006: 13). For example, the previous existence of the bicycle industry within a region gave a regional advantage for the emergence of the auto industry because of components produced by the same or closely related routines. Thus the bicycle and auto industries are an example of ‘related variety’ and greater related variety across sectors in a region, it is argued, is conducive to regional growth.[11]

Related variety offers a different concept of a historically evolving, regionally distinct cluster from the established, uniform cluster concept of Porter. Whereas Porter seeks to identify carbon copy clusters in multiple regions each constituted by the same linked sectors, the idea of related variety implies small groups of enterprises historically evolving that share common but regionally distinctive ‘organizational skills’ or routines. The concept of related variety is consistent with the empirical observation of ‘clustered diversity’ used by Martin to describe the two most innovative regions in the UK. He observes that the Cambridge ‘high-tech’ cluster is in fact made up of at least seven sub-clusters and that the South East economy, which appears highly diversified, contains several highly specialized clusters of innovative activity (2005: 29).

The application of the concept of routine to economic geography is an important step in integrating business organization into studies of regional economic adaptation. But can routine carry the heavy load to which it has been assigned? It does go inside the ‘black box’ and give distinctiveness and organizational integrity to the business enterprise. But it has a weakness. Routine is a static concept. It can not explain change in routine, where routines come from, or even what they are.

This critique is not new. Efforts have been made to extend the concept of routine a description of “stable patterns of organizational behavior” into a theory of organizational change. Zollo and Winter offer the concept of dynamic capabilities “…defined as routinized activities directed to the development and adaptation of operating routines” (2002: 1).[12] But the same authors make the candid and surprising comment, given its source: “…the literature does not contain any attempt at a straightforward answer to the question of how routines—much less where dynamic capabilities—are generated and evolve” (2002:9).

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[11] In a study of the Netherlands assessing the impact of related variety on growth Frenkel *et. al.* (2005) sectors were defined as related variety when they shared the same category in the sector classification scheme at the 5-digit level and as unrelated variety when they belonged to different sector headings at the 2-digit level. The study found that related variety was associated with employment growth in the period 1996-2002.

[12] Teece, Pisano and Shuen (1997) describe dynamic capabilities as “…the firm’s ability to integrate, build and reconfigure internal and external competencies to address rapidly changing environments”. This description substitutes the term competence for routine but leaves open the questions of what competences are, where they come from, and how they change.

On this point we disagree. While Penrose did not use the term capability its substance is captured in her concept of growth as "…an evolutionary process…based on the cumulative growth of collective knowledge, in the context of a purposive firm" (1995: xiii). Penrose elaborates a learning firm concept based on a distinction between resources and the productive services of resources. "It is never resources themselves that are the 'inputs' into the production process, but only the services that the resources can render".

Resources can be purchased in the market. In contrast the services that resources render a firm depend upon the distinctive experience and teamwork of its members:

> Experience…develops an increasing knowledge of the possibilities for action and the ways in which action can be taken by…the firm. This increase in knowledge not only causes the productive opportunity of a firm to change…but also contributes to the 'uniqueness' of the opportunity of each individual firm. (Penrose, 1959: 53).

Equally important, a firm is more than a collection of individuals: "it is a collection of individuals who have had experience in working together, for only in this way can 'teamwork' be developed" (1959: 46).

The direction of innovation or knowledge creation in any firm is "…closely related to the nature of existing resources (including capital equipment) and to the type and range of productive services they can render" (1995: 84).

She calls attention to economies, not of scale or size, but of growth created by new applications of unused productive services internally generated from previous successful applications. Inducements to expansion "…arise largely from the existence of a pool of unused productive services, resources, and special knowledge, all of which will always be found within any firm".

The innovation drive of the Penrosian firm is governed by an iterative dynamic in which firms seek to redeploy unused productive resources to incipient market opportunities and in the process deepen and differentiate their productive productive services. The learning experience renders yet new or refined productive services which triggers a new learning and market opportunity detection dynamic.

For terminological simplicity we follow George Richardson (1972) in using the term capability for productive services of resources. Capabilities, like productive services, cannot be developed alone or at once, they are cumulative and collective, they evolve with teamwork and experience and in the process knowledge is increased. Richardson extended Penrose's internal process of capability development to an inter-firm process in which firms specialize on core capabilities and partner for complementary capabilities.

The focus on organizational capabilities, experience, and skills at the enterprise level has a regional corollary. Production and technological capabilities, for example, are key concepts in this paper. Historically, shifts in regional industrial leadership can be explained in terms of the introduction of plants organized around new, advanced principles of production. Mass production, a capability anchored in the principle of flow, was a revolutionary new means of production that established a step-change in productivity and raised performance standards in cost by an order of magnitude. Equally important, from a regional perspective, the Ford plant was both a demonstration site and a learning center for application of the new principle of production. Engineers, managers, workers, and suppliers simultaneously constructed and learned the new production processes and the complementary skills all of which could be passed on to other firms and other industries.[13] Succeeding generations of engineers, managers and workers were, as if, plugged into roles within the production system without awareness of its origins or architecture.

While the Ford plant was revolutionary (and ultimately transitory), the principle of flow is enduring.[14] It became a source of regional competitive advantage wherever business enterprises met the challenge of a applying the principle to commodity sectors still laboring under pre-mass production methods. Even today, it remains a means of making a step-change in productivity within factories and regions that have not made the transition but are seeking to engage in high volume production.

However, advances in production capability can be incremental as well as transitional to new principles. A legacy of distinctive production capabilities constructed collectively and cumulatively over many new product generations and diverse applications and diffused into co-located firms is a regional resource that can not be easily replicated. Most importantly, such capabilities are a platform for a new round of product development initiatives.

Regions have distinctive technological capabilities as well. Seattle and Tacoma Washington, for example, is a region in which aircraft have been designed and developed for many decades and in which the associated engineering principles and practices are woven into the fabric of industrial life. Individuals plug into long established routines much as they do into a language community but their individual skills are as interdependent as the words in the language itself. Both are social as well as individual. They are ‘deep craft skills’ or ‘organizational skills’.

The regional renewal challenge is to either make the transition to more advanced capabilities and/or to convert already established capabilities and skills into new products, new enterprises, and new industrial sub-sectors. The agents of the transition and/or conversion are, in most cases, the business enterprises located in the region. A regional business system which includes networks of specialist enterprises with complementary capabilities is an organizational infrastructure which eases the entry of new enterprises. A new entrant can focus on a core capability and partner for

[13] For a detailed production capability spectrum that allows for firm and regional comparisons and assessments see Best (2001: Ch. 2).
[14] Other examples of regional or national industrial leadership created by the establishment of new principles of production and organization can be found in Best (1990 and 2001).

complementary capabilities; a rapidly growing company can tap skills and capabilities no longer required by nearby companies in declining markets.

At the regional level, industrial renewal is a systems integration process in that companies, capabilities and skills are reshuffled, reconfigured, and redesigned to seize market opportunities. In the process, the technological capabilities which were leveraged in the first place are advanced and deepened thereby reinforcing the regions competitive advantage. In this way technology-driven business enterprises act as vehicles by which regional capabilities are renewed.[15]

Thus a dynamic Penrosian capabilities perspective focuses attention on dynamic specialization processes by which new firms, sectors, 'industries', or clusters emerge and evolve. It implies that the long standing debate has been misguided: specialization and diversification are different parts of a single process. Specialization in capabilities enhances diversity in application and greater sector diversity enhances market opportunities for new product development which, in turn draws upon and renews specialized regional capabilities. At the same time product differentiation is the leading edge of industrial diversity. It evokes Jacobs growth perspective of increasing industrial differentiation based on the creation of new sectors.[16]

The challenge is to characterize distinctive regional capabilities. Unlike output and employment, capabilities are intangible. Nevertheless, they are real and, I argue below, subject to indirect characterization methods based on empirical inferences generated by application of a finely granulated technology taxonomy to companies and their products.

Research methodology

The empirical challenge is considerable. The presumption is that regional production and technology capabilities, while intangible, are embedded in the production processes and deep craft skills of a region and manifest in specialized groups of companies and the products they design and develop. We seek to 'discover' the underlying capabilities that, while hidden, impart locational advantage by examining tangible patterns of companies and products.[17] A study of capabilities requires a historical data set of real companies and

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[15] The biological analogy, admittedly imperfect, is to Dawkins distinction between 'replicator' and 'vehicle' (1989: 254). The business enterprise, like the body, is a mere vehicle; it is not replicated. Its function is to propagate the replicators. In the natural world, DNA molecules are replicators; they are the fundamental units of natural selection. Distinctive regional capabilities, not the business enterprises, are the basic unit of competitive selection across regions. But, as we have noted, the vehicles may be more or less successful in propagating the replicators.

[16] Jacobs distinguishes two growth processes (1969: 129). Preformative growth is a process by which all elements expand by the same increments; epigenetic growth is a process of growth through increasing functional differentiation much as the human grows from a simple embryo. Economies, she argues, growth by increasing differentiation.

[17] Our research method is similar to empirical studies of 'revealed' comparative advantage first proposed and conducted by Bela Balassa (1965). In these studies, underlying comparative advantage is interpreted by the examination of traded product statistics. Instead, we use measures of companies and products filtered

their products. Official data is no help for two reasons. First, companies are ahistorical and anonymous and second, the classification categories lack the granularity required to capture both differentiation and specialization.

To get inside the companies that populate a region, we have constructed vTHREAD (Techno-Historical Regional Economic Analysis Database) a historical database of approximately 55,000 public and private, high tech producers and their products.[18] The dataset includes the companies and the products they make and, most importantly, is organized in terms of a finely granulated technology taxonomy originally developed by CorpTech. The CorpTech technology product classification system has three major filters. Companies are grouped by 18 primary industry codes and 280 major product codes, which in turn support roughly 3000 technology-product applications.[19] This degree of granularity is requisite for 'discovering' technological capabilities and capturing both specialization and differentiation processes.

The research methodology is based on the proposition that the existence of a distinctive regional technological capability gives local firms a competitive advantage. Therefore, an inter-temporal grouping of companies in closely related technology-product domains is an indicator of an underlying regional capability. The regional capability itself is not observable or directly measurable, but it can be revealed by a study of groups of successful firms with similar technology-product characteristics. Individual firms may enter and exit, but the presumption is that at any point in time there is the critical mass required to sustain the new product development process and, with it, revitalize the underlying technological capabilities.[20]

Three propositions guide the analysis of industrial renewal presented here.

The first is a path dependence proposition. A region's production and technology capability legacy is a basis for regional competitive advantage. Today's firms can

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by a finely granulated technology taxonomy to reveal underlying capabilities which impart competitive advantage to firms in the region.

[18] The vTHREAD database is populated with a longitudinal file covering 1989 to the present, based on CorpTech data. The primary purpose of the CorpTech data set was to provide company information on private and public high tech companies in the United States. It was supplied quarterly to subscribers and included approximately 55,000 high-tech companies in the United States, including 5,000 in Massachusetts. Although the dataset is not constructed for scholarly purposes, CorpTech established a sophisticated data collection and research methodology, including quality control systems and consistency checks. The data base is longitudinal: firms in the data base were observed and measured over a number of years and their year-to-year records were then linked. CorpTech's data collection methodology had 8 phases: company identification using a variety of sources, telephone interview after which the companies products are coded, editing by senior researcher, data entry, internal proofing, machine check which applies numerous tests to each record, external proofing, and written verification of the record from the listed company.

[19] Details on the CorpTech taxonomy can be found in Best, Paquin, and Xie (2004) appendices A and B.

[20] Geographers have suggested various 'embedding frameworks' and 'learning mechanisms' by which industrial localization and clustering lead to distinct trajectories of innovation. See Bathelt, H., Malmberg, A., and Maskell, P. (2004). Hopefully application of the capabilities perspective presented here can more specifically characterize the distinctive knowledge domains of regions.

leverage distinctive capabilities and skills established by preceding companies and in the process advance them for succeeding product development generations. Here our focus is on inter-temporal evolution of regionally specialized capabilities. The challenge is to characterize these capabilities and their evolution.

The second is a cluster dynamics proposition. A region's capabilities are also shaped by dynamic, inter-firm, mutual adjustment processes. If the first proposition focused on the dynamics of regional specialization and the evolution of specialized groups, the second focuses on the dynamics of differentiation and transformation within and amongst specialized groups.

The third proposition is that regional specialization is shaped by both 'path dependence' and 'cluster dynamics' and that each is better understood within a framework that accounts for both.

The research challenge is to articulate and characterize a range of processes by which the pre-existing production and technological capabilities within a region are leveraged, adapted, integrated, differentiated, and reshuffled. The modus operandi is to first group a region's high-tech enterprises by a finely granulated taxonomy. The companies and the groups are then examined first in terms of in terms of capability 'path dependence' or inter-temporal, evolution of regional specialization and second in terms of inter-firm mutual adjustment processes by which the groups themselves are reconstituted by internal processes of differentiation and transformation.

An Industrial Laboratory: Lowell, Massachusetts

Lowell, Massachusetts is interesting location for examining industrial transition and renewal. Industrial renewal occurred not once but twice in recent times. And the two industrial renewals were remarkably different, at least in appearance.

In the beginning, Lowell was a textile city. The population of Lowell grew in synch with the nation's textile industry for nearly a century expanding from 2500 in 1826 to over 110,000 in 1920 (Gittell 1995). In the early 1920s, employment in the textile industry accounted for over 40 percent of all manufacturing in Lowell. But between 1924 and 1932, manufacturing employment fell by 50 percent (Flynn 1988: 277). Lowell did not recover from the Great Depression but employment began to grow in the 1960s primarily in low wage and declining industries.

The first post-textile era industrial renewal was led by a single company and a single industry. Wang Laboratories, founded in 1951, relocated to the city in 1977. In the peak years of the mid-1980s, Wang Labs employed over 10,000 workers in the Lowell labor market, accounting for approximately 10 percent of total employment and one-third of manufacturing employment in the local economy (O'Connell 1991a). But Wang transformed the industrial landscape only to collapse and double-digit unemployment returned. The Wang era ended in 1994 with the auction of the 15 acre, three-tower, 1.5 million square foot office complex for $525,000, approximately 1 percent of the $55 million cost to build the facility.

Lowell suddenly went from a success story to a recipe for industrial decline. Once more the sources of decline were attributed, properly, to excessive reliance on a single industry and an autarchic business model (Gittell 1995; Kenny and von Burg 1999; Saxenian 1994). The problem was that the minicomputer industry collapsed much more rapidly than the textile industry a half century before. Furthermore, this time around Lowell was, at least in appearance, virtually a single company town.[21]

But the story does not end here. Surprisingly to most everyone, both Massachusetts and the Lowell area enjoyed a decade of growth beginning in the early 1990s. The second renewal was not driven by the emergence and rapid growth of big, vertically integrated companies and it was not associated with the rapid rise of a single industry. Out of a population of roughly 120 high tech companies in the Lowell area in 2003, only one employed over 3000 and only two others employed over 2000.[22]

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The 60 high tech companies with 25 or more employees operating in the Lowell area in 2003 are shown in **Table 1** (another 60 had less than 25 employees in 2003). The immediate difference between the first and second high-tech boom decades in Lowell is obvious from a perusal of Table 1. Whereas the first renewal was driven by one firm and one sector, the second is better described as 'clustered diversity' (Martin 2005: 29), a combination of specialization and diversity. The sixty business units with over 25 employees have been separated into 5 major technology-defined groups of Instruments and Devices; Optics, Imaging and Photonics; Network Communication Equipment; Software Tools; and Factory Automation Equipment. Collectively these 5 groups employed nearly twice in 2003 in the Lowell area what Wang Laboratories employed in its peak years of 1985 and 1986.

Where did these companies and associated technology groups come from? Quite literally, many were founded closer to the Boston metropolitan region and moved out after reaching a certain size.[23] But Wang had done the same and the question of technological specialization remains. Why did the high tech companies which came to locate in the

[21] "By 1989, approximately one-third (35 percent) of the local labor market's employment was in manufacturing, with industrial machinery accounting for over one-half of the manufacturing jobs. Industrial machinery had become as important to Lowell manufacturing employment as textiles and apparel were at the turn of the century. Further, over 90 percent of the employment in industrial machinery was in one industry, office and computing equipment (SIC 357), which includes minicomputers. One firm, Wang Labs, accounted for the bulk of the local jobs in that industry" (Gittell 1995).
[22] We define the Lowell area as the 3 adjoining townships of Lowell, Chelmsford, and Westford.
[23] Lowell has benefited from its location at the intersection of Interstate 495, an outer ring road around Boston, and Highway 3, a short drive to New Hampshire.

Lowell area have this particular set of specializations? No one has claimed that this pattern or indeed any pattern of 'clustered diversity' was policy-driven.[24]

Clearly, the Lowell area is exceptional. But to date the contours of its sectoral composition and the sources of its industrial revival have not been explained. Perhaps the extremes of high-tech growth, collapse, and growth again offer secrets to a better understanding of regional specialization and innovation processes.

We turn now to an exploration of specialization dynamics using the high-tech companies of the Lowell area as an 'industrial laboratory'. We seek first to historic patterns of continuity and change in regionally distinctive production and technology capabilities and second to industrial dynamics of differentiation and transformation.

Path Continuity Dynamics

The concept of path dependence has been widely used by economic geographers to research the evolution of economic landscapes (Martin and Sunley 2006). While the emphasis has been on how regional economies can become locked into paths that lose dynamism, path dependence can also have an upside and contribute to regional industrial renewal. In these cases a region's legacy of distinctive production and technology capabilities are leveraged, integrated, differentiated and reshuffled to create new industrial sectors. In this section we interpret industrial renewal in the Lowell area in terms of specialization dynamics driven by business enterprises and anchored in the region's production and technology capability heritage.

While every successful company has developed a unique concept or product idea to distinguish itself in the marketplace, we can also find common patterns. We look first at common production capabilities and second at common technological capabilities.

Leveraging Production Capabilities

All 60 companies and every specialized technology group in Table 1 can be classified within the broad category of instruments, tools, and equipment. Not a single company does mass production or operates in consumer markets. In this all of the Lowell area companies reflect New England's specialization in production capabilities that can be traced back to the establishment of the principle of interchangeability at the Springfield Armory in the early decades of the nineteenth century and continuing up to leadership in tools and devices in the life science industries of today (Rosenberg 1972; Best 1990).

[24] Many of the companies have been around awhile. Of all 120 high-tech companies in the Lowell area in 2003, thirty-two were founded in the 1990s. Thirty-eight were founded in 1980s, but 23 go back to the 1970s, 8 to the 1960s and 5 to the 1950s. Of the 60 with 25 employees or more, 10 were established in the 2000s, 18 in the 1990s, 16 in the 1980s, 9 in the 1970s, 5 in the 1960s, and 2 in the 1950s.

The uniqueness, and surprising robustness, of New England's industrial economy has long been obscured by standard classification categories and codes. Since the rise of mass production and the consolidation of the automobile industry in the mid-West, New England's industrial experience has been examined through the lens of mass production. It always comes up short if not backward. The theme of industrial failure is illustrated with high volume, consumer industries, such as apparel and shoes, which did not survive the development of mass production capabilities in other regions.[25]

The conceptual lens of production capabilities reveals a different industrial landscape. Massachusetts' companies specialize in precision instruments, industrial equipment, and complex product systems. In fact, the historic lack of high volume production capability in New England was countered by the development of distinctive capabilities in complex product systems such as jet engines, missile defense systems, minicomputers, factory automation equipment, and 'backbone' switching equipment for the telecommunication carriers.[26] Massachusetts lacks a heritage in mass production engineering, consumer-oriented technologies and associated business organization capabilities; its strengths are in industrial-oriented technologies, precision and systems engineering, complex products and, as will be demonstrated, software tools.

From the production capabilities perspective, the high-tech growth periods did not represent a break with the past. Instead, the successful enterprises leveraged the region's distinctive production capability legacy and, in the process, renewed it. While the production capability threads go back, their applications were often in different and even newly established sectors. In all cases, the success stories have been innovative in new product development and technology management.

This casts a new light on Wang. Officially, the high-tech era in Lowell begins with Wang's move to the city in 1977.[27] Wang, the story goes, represented a break with the 'mature' industrial past of the region and signaled the transition to high tech (Glaeser 2005). Of course, this is partly true. But, from the perspective of the region's production capability heritage in instruments, toolmaking and industrial equipment, the high-tech

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[25] The claim that mass production capability is extremely rare in Massachusetts is resisted by many in Massachusetts, even many with technology backgrounds. They cite plants such as Gillette, Norton Abrasives (now a division of *Compagnie De Saint Gobain* of France), and Smith&Wesson. Unless they have been transformed recently, these are not examples of mass production but of mass batch production; these two production systems operate according to different principles (Best 1990: 147-161 and 2001): 28-40). While many Massachusetts' manufacturing plants have made impressive advances toward 'world class manufacturing' performance standards in cost, quality, and time; precious few have been transformed from 'mass batch' production methods to multi-product flow, cellular layout, and the synchronized of cycle times. Each company may have good commercial reasons to stick with mass batch production methods; in addition, they will not easily find the 'deep craft skills' in the region for, or even an understanding of, mass production methods.

[26] For example, and as will be shown below, Massachusetts companies supply complex switching gear, infrastructure equipment to the major telecommunication carriers; whereas Silicon Valley companies dominate the high volume, consumer electronic end of the market such as hubs and routers for business and homes (Best, Paquin and Xie 2004).

[27] "Wang's greatest gift to Lowell was its address", states William Taupier, the Lowell city manager who facilitated the move.

boom in Massachusetts did not begin as a clean slate or a *tabula rosa*. In fact, Wang's early history involved leveraging and re-"tooling" the State's instrument and tool making heritage. An ex-Wang 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 1960's, 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." Rick Bensene, Wang Laboratories: From Custom Systems to Computers", October 2001, updated June 2002, www.oldcalculatormuseum.com/d-wangcustom.htm

The Wang examples illustrates the dynamic specialization theme of continuity and change.[28] Before Wang there were machine tool and precision instrument makers. Wang seized the opportunity to marry machine tools with electronic controls which was itself an intermediate stage in the marriage of digital computing and control systems and the region's early industrial leadership in cybernetics.[29] Even here, the instrument making heritage was not lost; it was subsumed in the region's transition to complex product systems, a key element in the rapid growth of the defense industry in Massachusetts (Best 2001: chapter 5).[30] And, as we shall see below, Wang's imprint on the region can be found in companies thriving in the Lowell area today. [31]

Adapting and integrating technology capabilities.

The broad category of instruments, tools, and equipment can be broken down into the eight specialist technology groups shown in Table 1 by application of the second filter in the technology taxonomy. The Lowell area provides empirical support for the concepts of 'related variety' (Boschma and Frenken 2006) or 'clustered diversity' (Martin 2005). Furthermore, while the groups are technologically diverse, they share a common characteristic: they both leverage the region's technology capability heritage and integrate old and new technologies.

[28] Wang never sought venture capital but facing a cash crunch in 1959 it sold stock worth 25 percent of Wang Laboratories to Warner & Swasey in exchange for $50,000 and access to $100,000 in loans (Rosegrant and Lampe 1992: 116).

[29] For an excellent technical and historical account of control systems see Mindell (2002).

[30] Seen from the perspective of a heritage in industrial equipment, the computer revolution in Massachusetts was not a radical break with the past. In an important way it can be read as a renewal of the region's technological capabilities.

[31] The Wang effect has long outlived the company's existence in Lowell. Wang Laboratories not only directly trained thousands in hardware and software technological processes who have gone on to other firms but, according to Chancellor William Hogan, An Wang played a pivotal role in curriculum development at the University of Massachusetts Lowell by pressing for a major expansion in software engineering in the early stages of the minicomputer industry.

Thus instead of being victimized by being locked into computer technology with the collapse of the minicomputer industry, the Lowell area is also home to a small, closely related group that has successfully integrated computer and image processing technologies. Three (Bard, Zoll, and Mercury Computer Systems) operate in the rapidly growth medical devices sector in Massachusetts and one in detection systems.[32] They represent technology path adaptability in computer technology.

The largest, Mercury Computer Systems, Inc., has 600 employees and was established in 1982. Mercury Computer supplies embedded computer systems for MRI and CAT-scan OEM's (original equipment manufacturer) GE, Philips, and Siemens Medical Systems[33] and for defense applications.[34] It 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 UK, France, and Japan.

Sky Computer, established in 1980 and employing 100, supplies half the image signal processing computers for explosive detection systems that scan luggage at US airports. Sky's software compilers and development tools run on multiple systems in industrial, medical, and defense applications.

The legacy of the computer era is more in software than hardware. Here, too, we find technology integration involved long established capabilities. Microwave technology (the radar segment of the electromagnetic spectrum) began in the region during World War Two. It was the core technology that drove the early growth of Raytheon, the largest industrial employer in Massachusetts. Interestingly, the largest and oldest industrial employer founded in the Lowell area is a microwave integrated circuit manufacturer. Founded in 1958 and employing 3300 in 2003, M/A COM is the big player in a small group in the Lowell area that contributed to the advance of a technology capability trajectory for half a century. Originally known as Microwave Associates, it provided magnetrons to US Army Signal Corps. Reflecting a move into wireless telecommunications, its name was changed to M/A COM.[35] More recently, it has enjoyed a resurgence with the growth of mobile telephony.

The region's capability in microwave technology is not lost on leaders in the industry. In 2001, Microsemi Microwave Products, a $200 million public company headquartered in

[32] See Best (2006) for a case study of the rapid growth of the Massachusetts medical devices industry.

[33] Others in this category include Bard Electrophysiology (est. 1969, 150 employees) which designs and makes specialist computer hardware geared to electrophysiology for the medical industry.

[34] 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".

[35] M/A-Com is an example of a company that is hard to slot in a single primary technology code. Over time the Company has progressed from primarily a defense contractor, to a component producer, to telecommunications. It has always been a microwave integrated circuit designer and developer.

Irvine CA, established a presence in the Lowell area with the acquisition of New England Semiconductor. [36]

Optics is the specialist technology group with the longest legacy. The development of optics-related capabilities in Massachusetts goes way back to the early days of precision machining and the age of amateur astronomers.[37] Two optics technology companies in Lowell are particularly impressive.

McPherson (est. 1953, 50 employees) has 60 years of optics experience. McPherson's first product was a spectrometer for Air Force Cambridge Research Lab that was launched into space with an "Aerobe" rocket in 1954. Today it supplies the world's science labs with optics tools or precision measuring instruments. McPherson instruments vary from miniature to versions that weigh over 20 tons and span 70 feet. Its spectrometers measure electromagnetic radiation and enable scientists to investigate small wavelength regions of the electromagnetic spectrum. The Company's spectrographs fly in space rockets and allow scientists to record and search out ancient events in the universe.[38]

Barr Associates, Inc. (est. 1971, 350 employees) designs and manufactures 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.

Thus a regional optic and imaging technology capability can be traced back to the early days of Massachusetts industrial history, microwave technology to the Second World War period, and computer technology to the early postwar period. All have been renewed and adapted and can be found in Lowell area specialist groups of today. The collapse of the minicomputer industry did not signal the end of computer technology capabilities.

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[36] Microsemi also acquired Compensated Devices, Inc. of Massachusetts in August 2001 and, along with Microsemi's Watertown, Massachusetts operation, consolidated both in a newly outfitted facility in Lowell. http://www.microsemi.com/finance/presentations/AnnualReport2002.pdf.

[37] Other interesting and still operating optics companies in terms of history or attraction of foreign investment include American Optical Lens Company (est. 1832, 40 employees) and is located in Southbridge, MA; The O.C. White Co., a manufacturer of microscopes (est. 1894, 10-24 employees), located in Three Rivers, MA.; Dolan-Jenner Industries, Inc. (est. 1962, 120 in nearby Lawrence, MA). Dolan-Jenner makes optical inspection equipment, gauging systems, 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 Best (2001: 136). Foreign investment in photonics is considerable in Massachusetts. Of 55 photonics CorpTech listed companies in Massachusetts with sales of over $5 million, 14 are operating units with headquarters in the foreign countries: Germany 5, Japan, Holland 2, Italy, UK 2, Canada, France, and Switzerland.

[38] A unit of McPherson, Inc., Space Optics Research Labs. (est. 1962, 20 employees), manufactures optical components and systems including laser and optical equipment, and supplies optical manufacturing services to government and aerospace.

The basis of similarity of the specialist groups in Table 1 varies and overtime specialist groups are reconstituted, emerge and differentiate.

The regional capability to integrate technologies is central to the success of enterprises in complex product systems. [39] This has been expressed in products as diverse as jet engines, missile defense systems, semi-conductor equipment manufacturing, mini-computers and telecommunication network switching equipment. In all of these cases, the region has demonstrated a distinctive 'organizational skills' [production capability] in integrating a range of technologies within a single complex product system. Systems engineering was advanced with every product iteration. While these capabilities and skills were developed in integrated 'closed' technology systems they became a valuable resource for the hundreds of small specialist companies that seized market opportunities created by the transition to open standards and open system business models.

Differentiation and Transformation Dynamics

The examples in the previous section illustrated path continuity as the leveraging and renewal of a region's distinctive production and technology capability heritage. Here we turn to examples of dynamic specialization which combine capability path continuity with industry differentiation and transformation.

Network communications and software tools are the two largest and fastest growing specialist technology groups in the Lowell area. Both groups illustrate Jane Jacobs' theme that growth is a qualitative process of differentiation and transformation. Her famous example is the creation of the brassiere as a new product from a fragment of the apparel industry which fostered the emergence of a new industry and eventually a transformation of the New York City apparel industry(1969; 51-53).

Jacobs' differentiation theme resonates with Adam Smith's theory of innovation based on increasing specialization.[40] In both cases, previously existing industry activities undergo a process of internal differentiation and specialization. Whereas Smith emphasized the consequences of specialization on process innovation, Jacobs highlights the potential for transformation of an industry based on differentiation and the emergence of new sectors.

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[39] The greater Massachusetts region is unmatched in 'technological' systems integration capabilities that cut across computers, communications, and control systems, a heritage that predates 'organizational' systems integration. The region's specialization in 'systems integration' is traceable 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 US 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 (Hughes 1998: 17). 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.
[40] Smith linked specialization to the discovery process (Loasby 1991).

The network communication ‘cluster’ is the largest high-tech group in the Lowell area with 25 companies in 2003. It is composed of an equipment and a software tools group. Technological change, vertical disintegration, and deregulation came together in the 1990s to foster the transition of the telecommunications industry from a voice-centric to a data-centric environment. The development of the data-centric Internet was based on packet-switching technology. For data transmission, the legacy circuit networks, which assign a distinct path for the duration of the connection, were inefficient.

In a sentence, the telecommunications retailers (service providers to households and businesses) demanded equipment supply companies that could design and develop complex switches to meet the requirements both of the new platform technology and of compatibility with the installed circuit-switching system over a potentially long transition period. Not every region has had the capabilities to respond.

Telecommunication equipment making was not new to the extended Lowell region. The location in the 1930s of AT&Ts two-million square foot manufacturing site in nearby North Andover, signaled the establishment of large-scale telecommunication switching and transmission equipment production in the Merrimack Valley.[41] The plant built circuit-switching equipment to optimize massive volumes of voice traffic over the traditional Bell telephone system.[42]

The AT&T plant, which had become a Lucent facility, did not make the technology transition and was shut down at the end of the 1990s. But, like Wang and computer capabilities, the collapse of the Lucent facility did not signal the end of network equipment production capability in the region. Instead the Lowell area became the site of a large group of new, fast growing companies in the design and development of the Internet infrastructure and the associated transition to the new public network in telecommunications. But instead of one giant switch making company, a cluster of communication network companies emerged in packet-switching equipment and software systems.

The leader in the establishment of the new network switching equipment industry was Cascade Communications, established in 1990. Cascade designed and developed equipment that would allow installed networks to more efficiently handle data traffic. Its competitive advantage was to offer, in Ed March’s words: “ a single system platform to support multiple packet communications protocols; service providers can offer these services through one system without the need to build separate specialized networks” (2003). Cascade’s employment grew from 28 in 1993 to 400 by 1996 before being acquired by Ascend Communications of California in 1997.

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[41] This is a study in industrial renewal on its own as AT&Ts location decision was based on the available of a large industrially experience workforce due to the decline of the footwear industry in the region (Ed March).

[42] This section draws heavily from an Anticipating Technology Trends internal document written by Ed March and titled ‘Cascade Communications “Family of Companies”’ August 2003.

Equally important, Cascade Communications was an entrepreneurial firm that fostered techno-diversification via spin-offs within the region.[43] A whole "Cascade family of companies" evolved to meet the equipment needs of the new telecommunication service providers created in the wake of deregulation. The range of complementary technology products in which the Cascade 'family' of companies operated is shown in **Figure 1**, 'Post Cascade Communications Technology Differentiation'. While most were acquired or otherwise exited the industry, collectively these and associated firms developed a Massachusetts regional capability in IP (Internet Protocol) products and services required to move data, voice, and video over public networks.

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The region's technological advantage in network communications equipment both attracted and was reinforced by the entry of foreign telecommunication systems companies such as Seimens, Alcatel, and Nortel as well as Cisco Systems, the Silicon Valley newcomer. All acquired companies along Interstate 495 in Massachusetts.

The equipment makers are not the only enterprises in the region's telecommunications industry. As shown in Table 1, the region and the Lowell area are also home to a number of software companies that specialize in network communication systems. Some of these pre-dated the Internet and repositioned into network communications, most are new entrants. Once again we find specialization and diversity.

The software tools group is a second example of differentiation and transformation dynamics. It is composed of two sub-groups, network communication software and enterprise software tools. As shown in Table 1, both are new industrial sectors constituted primarily by small and medium size companies formed in the 1980s and 1990s. All of the fourteen network communication equipment companies were founded after 1995. Seven of the software tool companies were established in the 1980s and ten in the 1990s. Several companies grew to employ a hundred to several hundred or more employees including Kronos, Davox, Zuken, NetScout Systems, Universal Software, MatrixOne, Steleus, and Airvana. These companies were growing at exactly the same time that the network communication equipment companies were expanding and both sectors are software engineering intensive.

The Lowell area software tool companies can be distinguished from business services in general in that all are high tech, software engineering companies. They are functionally analogous to machine tool companies of the region's industrial past. Both specialize in products/services that enhance performance in companies independent of industry.[44]

[43] Details on each of the 11 Cascade 'family of companies' can be found in March 2003.

[44] Like the region's machine tool companies of the past, many of the software tool companies operate in global markets. A Japanese company, Zuken, established a Lowell Area unit Zuken USA in 1983 which grew to 500 employees. It specializes in concurrent design tools including CAD/CAM (computer-aided design/computer-aided manufacture) software for multiple brand workstations and sells to the engineering industry. Zuken USA has PCB (printed circuit board) design service bureaux in 10 countries and 100s of 'partners'. Established in 1994, MatrixOne, Inc. grew from 200 to 600 employees between 1999 and 2003 by offering product lifecycle management (PLM) services to manage global supply chains. It partners with

Collectively they supply a diverse range of business services to various industrial sectors. As their performance improves, it reinforces the historic tendency to increased vertical specialization in all business sectors.[45]

Many of the software tool companies began as equipment making companies. The largest is an example. Kronos, established in 1977, has become a 2300 employee, $350 million company that began with the founder's idea to put a chip into a mechanical time clock and thereby to bring computer technology to labor and payroll management and production scheduling. Its original attendance tracking technology platform was an electro-magnetic device; in the late 1980s, Kronos migrated to the PC, and in the early 1990s to LANS (local area networks) and WANS (wide area networks), followed by web-browser, visual factory technology. Along the way customers such as Dell Computer helped to reshape the 'time and attendance' product from a management tool for reducing labor monitoring costs to a workforce empowerment resource consistent with TQM (total quality management) and lean manufacturing.[46]

Most, however, are not large companies. **Table 2** illustrates an organizational feature of the open system business model: high rates of industrial churn. Churn, in this context, refers to the processes of entry, exit, and growth of firms within a sector or region. High churn, as evidenced by high rates of entry and of enterprise growth is an enabler of regional new product development, technological change and industrial transformation. Table 2 only includes companies with 20 employees or more.

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Industrial 'churn' is an indicator of regional systems integration capability.[47] Regional economies that have the capability to rapidly reshuffle and reconfigure capabilities and

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Tata Consultancy Services (Asia's largest software company) to establish a PLM Center of Excellence to offer Fortune 500 companies worldwide assistance in reducing new product development cycle times.

[45] In the early days of the industrial revolution, specialist machine tool making companies spun out of vertically integrated companies to form new groups of specialist machine tool companies. Analogously the information technology revolution has been accompanied by increasing vertical specialization accompanied by the emergence of software tool companies.

[46] Two other examples are Davox and Datawatch Corporation. Davox, established in 1981, (recently renamed Concerto Software, Inc.) began as a supplier of data concentration equipment and computer-voice telephone equipment primarily to call centers. With the acquisition of AnswerSoft, Davox enhanced customer interaction features and entered the Customer Relations Management (CRM) market with a product that combines telephony, fax, email, and the web. It employs nearly 500 with 300 in Massachusetts and sells to financial institutions, airlines, telecommunication providers, insurance companies, utilities, and retailers and has subsidiaries in Canada, UK, Mexico, Germany, Brazil, Japan, and Singapore. Datawatch Corporation began in 1985 as a designer and manufacturer of computer workstations for high security applications but pursued opportunities in business software by developing a distinctive capability in the use of information technologies for report writing. Rather than pursing information storage technologies, a Massachusetts specialty, Datawatch chose to focus on information use. This includes data extraction, mining and transformation across disparate databases and multiple platforms.

[47] This churn of enterprises counteracts the 'innovator's dilemma' of single companies as described by Clayton Christensen (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

skills to form new teams and take advantage of technology advances or new market opportunities have systems integration and reintegration capabilities.[48]

The principle of systems integration holds that the full effects of an advance in a sub-system are not limited to the sub-system or to the initial and obvious effects; they can include the creation of opportunity to redesign the system as a whole to achieve a step-change in global performance. potentially large architectural change feedback effects.[49] The idea of an 'open-systems' business model implies the decentralization and diffusion of design experiments across many enterprises and suggest an extension of the principle of systems integration from a firm to a regional system of mutually adjusting enterprises.

From a regional innovation point of view, the exit of firms is important. Capabilities and skills are released from declining applications and taken up by entering and fast growing firms. Companies like Digital Equipment Corporation, Wang Laboratories, and Lucent not only advanced technological capabilities, engineering expertise and IT-related skills in the region on a massive scale but created a capabilities and skills resource base that could be tapped by growing firms in succeeding and related sectors. This regional pool of high-tech resources fueled the burst of new firm activity and the human resource requirements of the next wave of high growth companies. It counters the negative lock-in effects of path dependence.

Summary

Regions that specialized in out-dated technologies and declining industries are rarely the location of emerging technologies and new industries. Massachusetts is an exception. Its economic resurgence led by the minicomputer industry was dubbed the 'Massachusetts Miracle'. In the late 1980s, the State once again lost out to competition from other regions and suffered a collapse of the minicomputer industry. But just as articles and books were being published on Massachusetts as a case study of industrial decline a decade long industrial revival was underway.

[The question is why, against the expectations of virtually everyone, did Massachusetts industry enjoy a revival following the collapse of the minicomputer industry?

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of firms with disruptive technologies much like the Upas tree poisons the seedlings of other species of plants around it; for the example of heavy engineering killing of alternative technologies and regional growth in Glasgow, Scotland, see Checkland (1981).

48 Churn is a regional organizational response to the inherent limits of even brilliant innovators to predict the technological future combined with and the inherent uncertainly of the specific technological future. The challenge 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".

49 Henry Ford, for example, did not see the introduction of electricity as a reduced cost of energy; he saw it as an opportunity to create a new production architecture. Ford's engineers redesigned the plant layout from functionally specialized departments to continuous flow lines. This demanded reengineering not only of the production process but the machines and work activities around a new principle (Best 1990).

Industrial renewal and resiliency processes are explored in this paper with the aid of a historical database of high tech companies of a sub-region in Massachusetts first dominated by textiles and later minicomputers.[50] The two century industrial history of Lowell is a location in which both industries were established, grew rapidly, and then declined. The crash of Wang Laboratories, located in Lowell, was dramatic and rapid. But while the City's biggest firm collapsed, the region proved resilient to the new competition of Silicon Valley and elsewhere as new sectors emerged and collectively grew rapidly.

Lowell is the beneficiary of the fecundity of the greater Boston area in the creation of new technologies and enterprises. But the Lowell area has become the address of a series of specialist technology groups which in turn have deepened the region's underlying technological capabilities.

The analysis is consistent with the idea of a regional innovation system as the source of growth in contrast to the technology transfer model of innovation in which local firms commercialize technologies that have been transferred from corporate, university, and government scientific laboratories (Broers 2005; Best NCA). In fact, the transfer metaphor has been appropriate in describing the emergence of the biotech industry. But it does not account for the processes of industrial renewal in the case of the Lowell area. The regional growth process is more complex and interactive.

The first dimension includes the regional production and technology capabilities and skill sets within which firms operate. A key to success was tapping into, leveraging, and extending the region's technological heritage. In fact, the long production capability threads in the form of experiential knowledge, technical expertise, and craft skills is a constant in specialist groups examined; they go back to early nineteenth century regional specialization in precision instruments, machine tools, and industrial equipment. We find also technology capability threads in, for example, optics, also going back to the early days but renewed when combined with the emergence of successive new technology knowledge domains in electrical and software engineering. Thus the past has not been lost, although it has been subsumed into more integrative technology knowledge communities.

The organizational characteristics of business and industry are equally central to the renewal and resiliency story in Massachusetts. Here we focused attention on transition from giant companies as the drivers of the growth process to the spread of an 'open-system', 'focus and network' model of business organization. The spread of the open-systems business model decentralized and diffused the design function and enhanced the new product development capability across a broad band of mutually adjusting enterprises. The example of network communication equipment shows how rapidly new technology mini-clusters can burst onto the scene. And the software 'tools' industry

[50] Unfortunately, the company dataset that populated vTHREAD was discontinued in 2005. Thus it is not possible to examine the effects of the Great Recession beginning in 2007 on Lowell industrial activity. We can say that there is no a priori evidence that the industrial innovation and sectoral transition dynamics examined here have declined in force.

illustrates the idea of enterprise 'churn', a Schumpeterian process of creative destruction in which resources are reallocated from under-performing to new and fast growing enterprises.

The new product development process is the mediator between business organization and technological capability. But it is more: it is at the heart of the interactive process by which regional capabilities are deepened and advanced. This is particularly important to an understanding of the cycles of renewal of industry in Massachusetts. Here at least, the technological capabilities that underlie new product development at the enterprise level and new sub-sector development at the industrial sector level are protean. But their successful development and application depends upon appropriately organized business enterprises. In turn, by designing and developing next generation product concepts that incorporate technical advances, firms cumulatively and collectively deepen the specialist engineering and craft skill 'know-how' in the region. These resources set the stage for future renewals.

What are the implications of the research methodology presented here for the development of a more general theory of industrial renewal and regional resilience?

The firm is the focus of attention because it is the driver of technological change, but not entirely within their own choosing. Instead, they are active agents within a complex industrial system which we characterize in terms of regional production and technological capabilities, and business organization. Together, these two dimensions can under certain circumstances establish a distinct model of industrial innovation: a regional innovation system in which industrial renewal operates at three levels.

At the individual firm level, industrial renewal is a process of successful new product development in response to changing market opportunities. But the new product development process is, at the same time, both a process of upgrading a company's capabilities, including technological capabilities, and a catalyst for cluster churn. These new, upgraded capabilities become resources for the next new product iteration. Successful products become resource magnets for growing firms.

At the inter-firm level, industrial renewal is about systems integration in that elements from established production and technological capabilities are recombined with new or other elements to form new products and sectors. The agency of change are a set of cluster dynamic processes starting with the new product development process of entrepreneurial firms and including enterprise spin-offs as the agent of technology differentiation and increasing specialization, inter-firm networks as the agent of technology combinations, and new firms as the agents of technological speciation itself enhanced by greater technological diversity. All of these processes are enhanced by the focus and network business model and the open systems model of industrial organization.

Vertical specialization and open-system organizational models are not necessary for industrial renewal but new company formation is mandatory. The role of new companies here is to force a crisis and response in older companies organized around earlier generation technologies and practices. Ironically, old companies are often haunted by new companies with product ideas that originated within but were not pursued by their own operations at an earlier time. In this way the new companies counter the social and organizational inertia that is inherent in companies that had enjoyed earlier business success. The new companies drag the old to play a role in advancing regional technological capabilities; without the crisis, the older companies can be a barrier to technological innovation and industrial renewal.

At the regional level, the potential for design experiments, capability and skill reconfigurations and serial regroupings of technology teams is enhanced by an open-system model of industrial organization. But 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. This specialization, in turn, fosters technological innovation and the potential for yet new enterprises and new configurations of enterprises. In the process, the regional technological capabilities, the source of regional competitive advantage, are revitalized.

Economic downturns, as well, are functional to regional renewal processes. Sustained growth is about capability development with periodic reshuffles forced by economic downturns, market changes, new competitors, or technological change. For this reason the path dependency story needs cluster dynamics just as cluster dynamics need path dependency of capability development and skill formation.

In all of these ways, the processes of renewal are at the same time the sources of resilience, more so at the regional than the individual enterprise level. The open-system business model is, in effect, an organizational form that turns what would otherwise be enterprise failure to adapt to new competitive pressures into a collective 'creative destruction' capability. Resources are shifted from declining to growing products and firms and the Penrosian firm learning effect creates opportunities and actions that counter the forces of organizational lock-in common to regions with closed-system business models.

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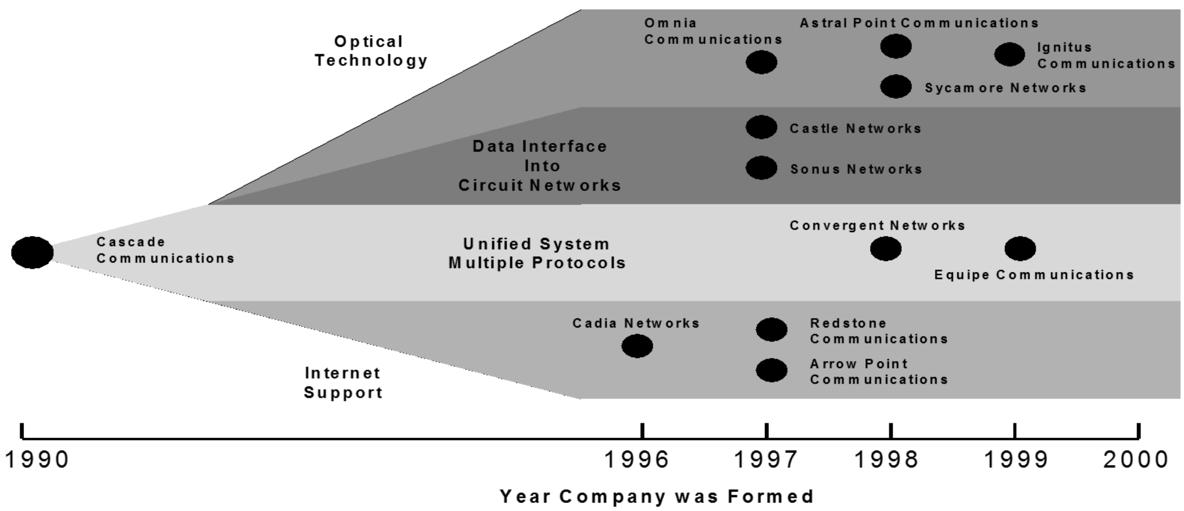
Table 1: Specialist Technology Groups in the Lowell Area

Company	Year* Founded	Empl. in 2003	Company	Year Founded	Empl. in 2003
Instruments and Equipment					
I. Test and Measurement					
Teradyne/GenRad/Sierra Research and Technology**	1960	1200	Thermo-Electron /KeyTek Instruments	1975	90
ENSR	1968	1267	Thermo Moisture Systems Corp.	1976	150
Assurance Technology	1969	90	Ionpure Technologies	1989	200
ESA	1970	86	Thermo Detection/ Thermedics Detection Inc.	1991	75
II. Factory Automation Equipment					
Styletec	1970	25	Innovative Products and Equipment	1980	45
Brooks Automation	1978	2500	Bull Electronics (acquired & merged into Celestica in 2001)	1987	165
III. Microwave Integrated Circuit					
M/A-COM	1958	3300	Hittite Microwave	1985	150
Microsemi Microwave Products	1985	70			
Optics, Imaging, Photonics					
IV. Optics Tools and Systems					
McPherson	1953	50	Optelic US	1985	70
Minuteman Labs	1967	40	Diamond USA	1990	150
Dielectric Sciences	1970	35	Cynosure	1991	150
Barr Associates	1971	350	Konarka Technologies (photonics)	2001	25
Shafer Corp	1972	44			
V. Digital and Signal Image Processing***					
Bard Electrophysiology	1969	150	Zoll	1980	844
Sky Computer	1980	100	Mercury Computer Systems	1982	600
Network Communications Equipment					
VI. Network Equipment					
Integral Access	1996	70	Astral Communications	1998	180
Nortel Networks	1997	250	SnowShore Networks	2000	45
Netnumber	1997	29	Storigen Systems	2000	65
Captivate Networks	1997	93	Mintera	2000	43
Sonus Networks	1997	497	WaterCove Networks	2000	110
Sycamore Networks	1998	400	Narad Networks	2000	50
Convergent Networks	1998	300	Airvana	2000	100
Software Tool Companies					
VII. Network Communications					
NetScout	1984	335	Quallaby Corp	1996	65
Steleus Inc.	1985	150	Brix Networks	1999	50
Biscom	1986	60	SavaJe Technologies	2000	50
OpenPages	1990	50	Amperion	2001	65
Universal Software	1992	140	Acopia Networks	2002	65
Softlinx	1993	25			
VIII. Enterprise Software Tools					
Kronos	1977	2375	Datawatch	1985	100
Davox	1981	470	MatrixOne	1994	600
Zuken USA	1983	500	Mission Critical Linux	1999	85
Iris Associates	1984	450			

*Most companies were founded closer to Boston but subsequently relocated to the Lowell area.
** The 1200 employment number exaggerates the presence of Teradyne and GenRad in the Lowell area. Teradyne acquired Lowell area Sierra Research and Technology (est. 1984, 35 employees) and GenRad (est. 1915, 500 employees in MA) in 2001 and moved its Assembly Test Division from Boston to Westford in 2002 before relocating again to North Reading in 2003.
*** All of these companies have medical device products, as do a number of companies in other technology groups including ESA and Teradyne.

Figure 1: Post Cascade Communications Technology Differentiation



Source: Edward March 2003.

Table 2: Entry and Exit of SOF Firms in Lowell Area, 1996-2000

(employment in firms with over 20 employees)

Company Name	Year Formed	1996	1997	1998	1999	2000	2001	2002	2003
Voicetek Corporation[i]	1981	120	175	Relocated to CA					
Gartner Group Learning[ii]	1987	N/A	66	Relocated to IL					
Mehta Corporation[iii]	1991	85	80	33	Relocated to NJ				
Spacetec IMC Corporation[iv]	1991	N/A	N/A	76	Relocated to WA				
EDS-Scicon, Inc.[v]	1984	30*	15*	70	100	100	Relocated to TX		
Quickturn Design Systems, Inc.[vi]	1993	25	25	39	45	45	45	45	Relocated to CA
Adra Systems, Inc.[vii]	1983	190	65	Relocated to other MA location					
ProMetrics Software, Inc.[viii]	1982	85	85	10	Relocated to other MA location				
Gulf Computer, Inc.[ix]/HCL Tech. (2002)	1979	200	200	200	Relocated to other MA location				
e-StudioLive, Inc.[x]	1971	10*	10*	18*	18	55	52	Relocated to other MA location	
Connolly International, Ltd.[xi]	1991	25	25	25	Exit TEL				
Quallaby Corp.[xii]	1996	N/A	N/A	N/A	N/A	90	Exit TEL		
NextPoint Networks, Inc.[xiii]	1996	N/A	N/A	N/A	66	66	Acquired by NetScout		
Iris Associates, Inc.[xiv]	1984	96	160	350	350	350	500	Acquired by IBM	
ONTOS, Inc.[xv]	1985	60	60	60	40	40	Out of business		
Viridien Technologies, Inc.	1997	Entry	N/A	N/A	N/A	120	60	Out of business	
Vikor, Inc.	1999	Entry	Entry	Entry	N/A	N/A	45	14	Out of business
Kronos[xvi]	1977	N/A	N/A	N/A	N/A	COM	COM	COM	2374
Concerto Software Inc. (PKA: Davox Corp.)[xvii]	1981	N/A	300	300	300	398	400	470	460
Tek Microsystems[xviii]	1981	N/A	N/A	N/A	N/A	N/A	N/A	N/A	35
Zuken USA, Inc.	1983	N/A	N/A	N/A	N/A	N/A	500	500	500
NetScout Systems, Inc. (PKA Frontier Software Dev.)	1984	50	140	190	220	220	364	355	340
Datawatch Corp.	1985	N/A	N/A	N/A	230	230	175	98	91
Biscom	1986	TEL	TEL	TEL	TEL	TEL	TEL	TEL	60
Digital Voice Systems[xix]	1988	N/A	N/A	N/A	N/A	N/A	20	20	20
SoftLinx, Inc.	1993	20	30	30	30	30	40	40	25
Universal Software Corp.	1993	N/A	N/A	N/A	N/A	N/A	140	140	148
MatrixOne, Inc.	1994	N/A	N/A	200	350	366	500	600	450
Trix Systems Inc.	1994	23	12	12	16	16	17	17	27
Steleus Group[xx]	1995	N/A	N/A	N/A	N/A	N/A	N/A	N/A	150
Brix Networks	1999				Entry	N/A	N/A	66	65
Mission Critical Linux, Inc.	1999				Entry	75	75	8	8
Airvana	2000					Entry	N/A	N/A	100
SavaJa	2000					Entry	N/A	N/A	50
Amperion	2001						Entry	N/A	65
Acopia	2001						Entry	N/A	65

Lowell area includes the adjoining townships of Lowell, Chelmsford, and Westford.
N/A: data Not Available; OOB: Out of Business; PKA: Previously Known As
Exit followed by a State abbreviation or company name signifies relocation outside of Lowell area.
TEL and COM signifies the primary industry code for company for the year.

[i] Acquired and merged into Aspect Telecommunications Corp., San Jose, CA in 1998.
[ii] Moved to Lowell area in 1997; acquired and merged into Illinois-based National Education Training Group in 1998.
[iii] Moved to NJ in 1999.
[iv] Acquired and merged into Labtec Enterprises Inc. Vancouver, WA in 1999.
[v] Moved to Lowell area in 1998; acquired and merged into EDS Corp. in 2001.
[vi] Acquired and merged into Cadence Design Systems CA in 2003
[vii] Moved to Tewksbury, MA in 1998.
[viii] PKA Digitech; acquired by parent ProMetrics Ltd. in 1991. UK Moved to Athol, MA in 1999; 10 employees from 1999 to 2003.
[ix] Parent is HCL Technologies, India. Both LangBox Division (founded 1994) and Spartacus Technologies Division (founded 1981) moved to Quincy, MA., in 1999. Renamed HCL Technologies (Mass.) in 2002.
[x] Moved to Lowell area from Burlington MA in 1999 and relocated to Tewksbury in 2003 and downsized to 30 employees.
[xi] 25 employees every year between 1996 and 2002 and 14 in 2003; industry code changed from Software to Telecommunications in 1998. (??Acquired and merged into Thompson Corporation, Canada.
[xii] Moved to Lowell area in 2000 from Burlington MA; became TEL in 2001.
[xiii] Acquired and merged into NetScout in 2001.
[xiv] Merged into IBM in 2002.
[xv] Moved to Andover, MA in 2001 and out-of-business in 2002.
[xvi] Moved to Lowell area in 2000 from Waltham MA and repositioned from COM to SOF in 2003. Employed 1200 in 1996 and 2000 in 2001.
[xvii] Moved to Lowell area from Billerica, MA in 1993.
[xviii] Moved from Burlington MA in 2003.
[xix] Moved to Lowell area from Burlington, MA in 2001.
[xx] Acquired by Tekelec of CA in 2004.