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Discovering Regional Competitive Advantage: Massachusetts High-Tech

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In recent times, Massachusetts has surprised many commentators by its ability to continuously reinvent itself as a successful regional economy. In this paper, we seek to penetrate the region's surprising resilience and better understand regional specialization, growth, and decline. We deploy a historical database of high-tech companies designed to conduct regional technology mapping exercises. We seek to advance both theoretical and empirical knowledge of regional competitive advantage along with a related set of concepts. These concepts include Marshallian externalities, regional technological capabilities, "self-sustaining clusters," and regional innovation systems. We previously presented results from an empirical investigation of "self-sustaining" technology "mini-clusters" in a sub-region of Massachusetts.[2] Here we interrogate the database using a set of regional competitive advantage indicators and extend our focus to the State of Massachusetts and, for comparison purposes, California's Silicon Valley.

The Massachusetts economy defies explanation. Historical narratives use terms such as "decline," "surprise," and "amorphous." Decline is the presumed default condition. Massachusetts is the economic center of a region that once enjoyed leadership in long-gone large-scale industries such as textiles, footwear, and, more recently, minicomputers. Job losses can be sudden and deep: one-third of Massachusetts' manufacturing jobs

[1] The authors thank Jay E. Kahrman for research assistance and Edward March for sharing his insider knowledge of the telecommunications industry and for Figure 3. The Chancellor's Office of the University of Massachusetts Lowell provided financial support for building the database used in this paper.
[2] See http://www.thebhc.org/publications/BEHonline/2003/Best.pdf

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URL: http://www.thebhc.org/publications/BEHonline/2004/BestPaquinXie.pdf

evaporated during the crash of 1986-1992, and 200,000 jobs were lost during the recession of 2001-2003.[3]

The decade-long growth rebound in the late 1970s and early 1980s led by the minicomputer industry, was characterized as the Massachusetts "Miracle." It was a surprise. The resurgence of the 1990s was equally unexpected. The commonplace image of the region as one of long-term structural decline was overlaid by an image of an innovation economy based on unrivaled R&D (Research & Development) strengths in universities, particularly MIT (Massachusetts Institute of Technology), and a robust new firm creation infrastructure funded by a thriving venture capital industry.[4]

Massachusetts certainly suffers during downturns with job losses and public budget cutbacks more severe than elsewhere in the United States. However, the region also seems to be unrivaled in its capacity to create new industries and regenerate itself economically. The paradoxical result: Massachusetts has both a large labor force migration outflow and a higher per capita income than all but two states.[5]

The questions remain: Will the sustained expansions of the Massachusetts "miracle" years and the resurgence of the 1990s be repeated? Will new industries emerge or grow sharply to once again drive growth?

Caught by surprise in the past, few economists risk a prediction about the underlying strength of the Massachusetts economy. A comment by Paul Krugman, braver than most and a major contributor to economic geography suggests a good reason for trepidation[6]: "...we have...an "amorphous economy," in which it is hard to find any focus. New England is clearly doing very well selling *something*; but what?"[7]

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[3] Massachusetts lost 209,200 positions in the 3-year period to Jan. 2004 or 6.2% of its jobs, the largest percentage of any state according to the U.S. Bureau of Labor Statistics. http://data.bls.gov/cgi-bin/dsrv, accessed October 25, 2004.

[4] For an excellent annual report on innovation in Massachusetts, see *Index of the Massachusetts Innovation Economy* published by the Massachusetts Technology Collaborative, www.masstech.org; accessed October 23, 2004

[5] In every year between 1990 and 2002 Massachusetts lost more people than it attracted (excluding international immigrants) and suffered a net loss of 213,000 domestic out-migrants (Robert Nakosteen, Michael Goodman, and Dana Ansel, *MASS.migration*, Boston, 2003 (www.massinc.org) accessed October 23, 2004. Massachusetts ranks in the top 3 states in per capita income according to the Bureau of Economic Analysis, http://www.bea.gov/ accessed October 23, 2004.

[6] "...I have spent my whole professional life as an international economist thinking and writing about economic geography, without being aware of it"; Paul Krugman, *Geography and Trade* (Cambridge, Mass., 1991), 1.

[7] Paul Krugman, "The Future of New England" in *Engines of Enterprise: An Economic History of New England*, ed. Peter Temin (Cambridge, Mass., 2000).

Krugman opines the "amorphous" character may be a consequence of the data we collect. However, he also suggests some concepts that could focus the image:

> ...despite all that I have said on behalf of amorphousness, in the end a region does have a set of *core competences* that give it a hard-to-measure but real distinctiveness. ...New England probably is driven by a few *self-sustaining clusters* of activities, which do not appear in our data only because we collect the data badly. Indeed, one might guess that the area's investment activities, its remaining computer industry, its exportable business services, and so on all reflect a common set of Marshallian *external economies*. If so, the question is whether the region's advantages will persist....[8]

Clearly, the data we collect and the theoretical concepts we use to interpret economic performance are interrelated. Can core competences and self-sustaining clusters be characterized, identified, discovered, or in some way measured? What kind of data would help sharpen these concepts and enrich our understandings of the sources of regional growth and decline in Massachusetts?

Theoretical Motivation

In this paper we seek to conceptually and empirically support Krugman's conjecture that "self-sustaining clusters," a "common set of Marshallian external economies," and a "set of core competences" are useful in making sense of New England's industrial experiences including its "surprises." The motivation is to embed these concepts in the capabilities perspective, a conceptual framework rooted in classical economics, but one in which organization and technology are also central to the story of industrial development and change.

The term "regional core competence" is closely akin to the theory of comparative advantage, which is as old as the discipline of economics. The idea of comparative advantage is that wealth can be advanced by specialization and exchange. In classical economic theory, the sources of comparative advantage are located in relative factor endowments in the form of land, labor, and capital. The theory is based on certain assumptions such as the lack of increasing returns to scale, technological change, and path dependency.

In recent years, the related concept of "competitive advantage" has gained widespread currency in business organization and management literature. It is consistent with the emergence of the rival "capabilities" perspective of industrial development and change. The central idea of competitive advantage is that the source of business success is the

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[8] Krugman, "The Future of New England," 273-5, emphasis added.

development of "core competences" or "distinctive capabilities." Capabilities are organizational accomplishments that take time and teamwork to develop.

The capabilities perspective focuses attention on the application of principles of production and organization that enable companies to develop markets, execute strategies, and sustain market share. Ford's innovative application of the principle of flow and Toyota's development of the Just-in-Time production system are examples of a step-change in production capabilities and productivity. The simultaneous development of the multi-divisional (M-form) business model by General Motors, DuPont, Jersey Standard (later Standard Oil), and Sears was an organizational step-change that established an organizational platform from which a strategy of product diversification could be executed.[9]

Closely related to production capabilities and business organization, technology (and its close associate, technology management) is a third form of organizational capability. However, technology differs from the other forms in two related ways. First, technological capabilities are inherently dynamic: they are continuously reshaped with every iteration of the "capability and market opportunity" cycle.[10] Sometimes, the change is to a "next generation technology"; other times it involves the integration or re-integration of two or more technologies as part of new product development. Second, technology capabilities are unique: they impart distinctive industrial signatures or fingerprints. Thus, technological capabilities are marked by both change and continuity. Their evolution is regionally path-dependent. Unlike production and organizational principles, technological capabilities are different everywhere.

For these reasons, observations of developments in technological capabilities are important to the dynamics of regional specialization. We argue that regional core competence is about distinctive regional technological capabilities that have been cumulatively and collectively developed across enterprises over time. In fact, they are the elusive substance in the "externalities" that figure so prominently in market-

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[9] Alfred D. Chandler, Jr., *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, Mass., 1977).

[10] For Edith Tilton Penrose the dynamic was between "productive services" and market "opportunity," *The Theory of the Growth of the Firm*, (first edition, 1959; New York, 1995). Penrose illustrates the productive services and market opportunity dynamic and the development of cellulose technology in "The Growth of the Firm—A Case Study: the Hercules Powder Company," *Business History Review* 34 (Spring 1960): 1-23.

centric theories of localization.[11] This is the terrain of the dynamic capabilities perspective applied to regional economies.[12]

The dynamic capabilities perspective we put forward is a conceptual framework that integrates internal dynamics of the firm with regional specialization dynamics. The starting point is the entrepreneurial firm, the driver of industrial change. The entrepreneurial firm is defined in terms of an ongoing iterative dynamic between distinctive capability and market opportunity.[13]

Integral to the internal dynamic is the notion that the very act of successfully responding to new market opportunities creates new capabilities. Extending the analogy of the internal dynamic of the entrepreneurial enterprise to the region suggests an inter-firm dynamic in which increasing specialization by one firm creates opportunities for specialization by other firms. In other words, the successful fulfillment of a market niche creates new market niches.[14]

Successful regions, like successful firms, have core competences or distinctive capabilities that impart competitive advantage. Like all capabilities, the regional variant takes time and teamwork to develop, is not easily imitated, and cannot be purchased in the marketplace.[15]

An example of a candidate for regional technological capability that has been cumulatively and collectively developed is turbine technology in New England. The first engineering experiments in America were conducted in Lowell, Massachusetts to advance the efficiency of water turbines to generate power. Deep craft skills in turbine technology were fostered as the applications shifted from waterpower to electric power and jet engines. Design and development work for jet engine turbines was highly concentrated in New England at least until the 1980s. Others candidates include optics and precision engineering.

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[11] Paul R. Krugman bemoans the tendency to assume externalities in explanations of regional specialization in *The Self-Organizing Economy* (Cambridge, Mass., 1996), 23.

[12] Whereas production and business capabilities are about step-changes in economic performance, technological capabilities focus attention on the ongoing dynamics of specialization.

[13] Dynamic capabilities, at the enterprise level, are defined as the organizational and production methods (including technical aspects) that enable a company to develop new products and processes in response to market opportunities and scientific advances. See David Teece and Gary Pisano, “The Dynamic Capabilities of Firms: An Introduction,” *Industrial and Corporate Change* 3 (1994): 537-566.

[14] Brian Arthur, cited in M. Mitchell Waldorp, *Complexity: The Emerging Science at the Edge of Order and Chaos* (New York, 1992), 119.

[15] The term teamwork is more appropriate to building capabilities within firms than regions because of the multiple independent agencies (governmental, educational, business) required to build regional capabilities. Nevertheless, the processes of cooperation and consensus-building that underlie successful organizations are management challenges in both arenas.

Such regional technology capabilities are intangible; they are embedded in the production processes and deep craft skills of a region, and are manifest in distinctive industrial sectors or technology-based clusters, and product profiles. The underlying distinctive capabilities give a region "organizational" location advantage. At the same time, participants can be easily take distinctive capabilities and associated skills for granted.

The empirical challenge is to audit and characterize a region's technological capabilities. Capabilities, like production factors are highly intractable to measurement. However, unlike production factors, unique capabilities are reflected in distinctive products, and dynamic capabilities are reflected in evolving product profiles.

The CorpTech Data Set

The core data set comes from CorpTech, established in 1986. The CorpTech dataset is the most current source of information on small, newly-formed companies active in high-tech fields. The current database has over 50,000 U.S.-based, high-tech business establishments, large and small, publicly listed and unlisted, self-contained companies, and independent divisions of a parent company. It includes many new startups and private companies missed by other databases.[16] Firm-level information includes location, number of employees, year of founding, country of ownership, and a product profile that that reflects a finely-granulated technology classification system.

The technology product-classification system has three major filters or layers. Products are categorized by 18 major and 280 sub-major technology categories, which in turn support 3000 technology-product applications. The 3-level classification system is illustrated for Telecommunication and Internet technology products in Appendix A.

Appendix B illustrates the granularity of the CorpTech classification system by comparison with SIC (Standard Industrial Classification) and NAICS (North American Industrial Classification System). This Appendix lists the product categories encompassed by SIC 3669 and NAICS 33429. Six major CorpTech primary industry technology categories are represented in the first filter, 16 CorpTech technology sub-segments in the second filter (for example, DEF-TS, TAM-SS), and 79 CorpTech technology product areas (for example, DEF-TS-C, TEL-NW-CS) in the third filter.[17] SIC and NAICS codes operate at a level of aggregation that

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[16] CorpTech, a division of OneSource Information Services, recently began offering a historical series that goes back to 1990. The historical series makes it possible to observe when, how, and over what time period technology trends that have since borne fruit emerged.

[17] The acronyms are defined as follows: DEF-TS (defense training simulation equipment), TAM-SS (test and measurement; security/safety equipment), DEF-

makes it extremely difficult to account for technology product specialization.

The CorpTech dataset does not include technology capabilities, for good reason. Capabilities are not tangible or observable. However, a company's product profile, mediated by a technology taxonomy system can serve as a proxy for capability. Because firms and the portfolio of products they make over time are observable and measurable, a company's underlying technological capabilities, in principle, can be inferred, interpreted, and mapped from their product profiles. Furthermore, by grouping firms within a region into similar technology product codes we have a tool to characterize specialized technological capabilities that underlie regional competitive advantage.

Developing the historical database is critical to the task of empirically validating and enriching the concept 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, dynamic capabilities are what enable firms to create new products and processes to both anticipate and respond to new market opportunities. Our method is to generate evidence in the form of historical trails left by firms' entry and exit and by sequential product iterations of enterprises in related technology domains. These trails, based on the finely granulated technology taxonomy, are a manifestation of the progression of hidden specialized technological capabilities that enable and persist through various product iterations over time.

Empirical Analysis

Figure 1-1 is an application of the first filter of the CorpTech classification to show companies founded in Massachusetts by all 18 primary technology sectors by decade. Figure 1-2 combines the closely related sectors into groups.[18] For example, the equipment and instruments group combines factory automation, testing and measurement, manufacturing equipment, and subassemblies and components. This group exhibits continuity in the decadal rate of new firm creation over 5+ decades. Computer hardware, a closely related technology sector, became an important source of new firm creation in the 1970s and 1980s before dropping off; software, on the other hand continued to be a major generator of new firms in the 1990s. The telecommunication and Internet sector grew rapidly to become the leader in the creation of new firms in the 1990s.

TS-C (combat simulation systems), and TEL-NW-CS (telecommunications; networks/internet equipment/components; data network switches).

[18] The criteria used for grouping varies: the equipment and instruments combines sectors that can be traced to the region's machine tool and precision engineering heritage; the life sciences group includes health related sectors; and the advanced materials includes photonics.

The life-science group combines the health-related sectors of medical devices, pharmaceuticals, and biotech. Medical devices, while always a presence, grew sharply in the 1980s before being overtaken by biotech in the 1990s as the major generator of new firms in this group. Medical devices, like computers, could be located within the equipment and instruments group, reflecting Massachusetts' strength in this category. A smaller group, advanced materials including photonics, also has an important presence in Massachusetts. Finally, the "other" group combines the technology sectors with a lower rate of new firm creation.

Figures 1-1 and 1-2 are not measures of the size of sectors in employment or sales, simply the number of firms founded per decade by primary industry code. Raytheon, the largest industrial employer in Massachusetts with 78,000 employees globally in 2002, is a defense contractor founded in 1922. Calculations for enterprise location quotients (ELQ) for selected industrial sectors in Massachusetts, California, and the Route 128/495 and Silicon Valley regions are shown in Table 1. Enterprise location quotients (ELQ) are defined as the ratio of high-tech firms in a specific industrial category within a region to the country divided by the ratio of population in the region to population in the nation. As shown in column 1, industrial sectors are defined at the second and third levels in the CorpTech hierarchy and for 4-digit SIC codes.

Massachusetts is particularly high in data network switches (TEL-NW-CS), communications control software (SOF-CS-C), and digital transaction-based Internet services (TEL-IF-D). California, at the state level, has relatively small enterprise location quotients, with the highest ratios in two telecommunications networks/Internet product codes (TEL-NW-CH and TEL-NW-CS).

However, by focusing attention on the regions frequently described as Route 128 and Silicon Valley we get somewhat different results. The highest ELQ for Route 128 in Table 1 is still data network switches (TEL-NW-CS) with a ratio of over 8 followed by the closely related communications control software (SOF-CS-C). Strikingly, two of the three highest ELQs for Silicon Valley are in the same technology product categories.

However, Silicon Valley's ELQ for semiconductors/devices (SUB-SE) is nearly 3 times that of Route 128. The semiconductors/devices (SUB-SE) companies with more than 2,500 employees in California and Massachusetts are shown in Table 2. The results indicate and reflect a major difference between Massachusetts and Californian high-tech industries. While Silicon Valley has many large component producers, Massachusetts has strikingly few, big or small. Analog Devices is the only Massachusetts company with SUB-SE products with over 2,500 employees with a SUB (subassembly and components) industry code; California has 16 in the same category with over 2,500 employees (see column 5).

FIGURE 1-1
Number of Technology Companies in Massachusetts by Decade Founded using 4Q03 CorpTech Taxonomy

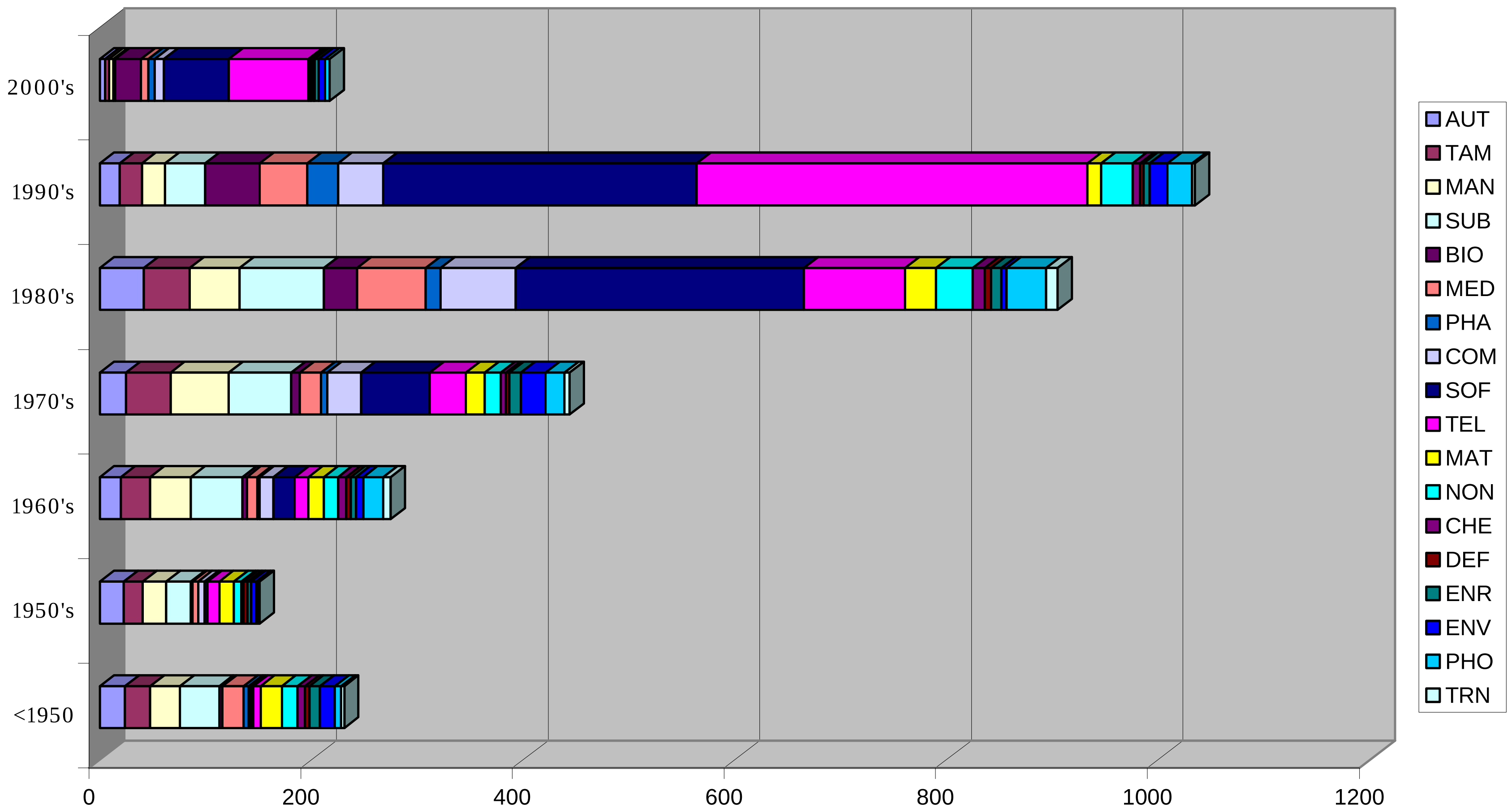

FIGURE 1-2
Number of Technology Companies in Massachusetts by Decade Founded using 4Q03 CorpTech Taxonomy

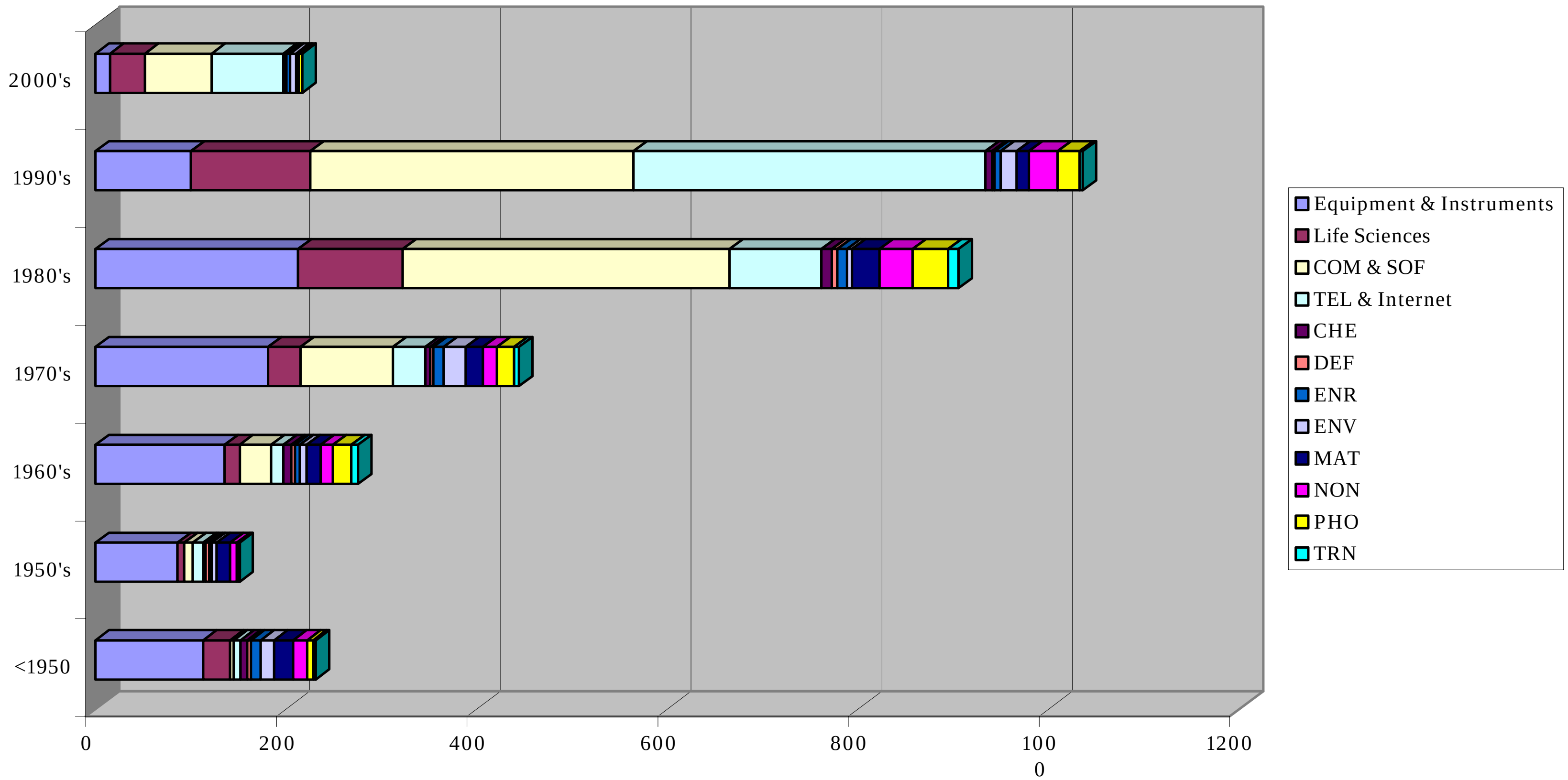

TABLE 1
Enterprise Location Quotient: Massachusetts vs. California

Sub-segment	Description	US		Massachusetts State			California State			Route 128/495 Region			Silicon Valley Region		
		Num of Firms	Num of Firms Per Million People	Num of Firms	Num of Firms Per Million People	ELQ	Num of Firms	Num of Firms Per Million People	ELQ	Num of Firms	Num of Firms Per Million People	ELQ	Num of Firms	Num of Firms Per Million People	ELQ
SIC 3661	Telephone and Telegraph Apparatus	860	3.07	64	10.30	3.36	265	7.73	2.52	53	15.16	4.95	104	21.46	7.00
SIC 3663	Radio & TV Communications Eqp	1297	4.62	86	13.85	3.00	370	10.79	2.33	64	18.31	3.96	141	29.09	6.29
SIC 3669	Communications Eqp, NEC	1652	5.89	132	21.25	3.61	486	14.17	2.41	114	32.61	5.54	211	43.53	7.39
TEL-NW-CS	Data Network Switches	170	0.61	21	3.38	5.58	66	1.92	3.18	17	4.86	8.02	35	7.22	11.92
SOF-CS-C	Communications Control Software	742	2.64	79	12.72	4.81	235	6.85	2.59	64	18.31	6.92	133	27.44	10.37
TEL-IF-D	Digital Transaction-based Internet Services	2893	10.31	271	43.64	4.23	701	20.44	1.98	248	70.94	6.88	352	72.62	7.04
SOF-CS	Communications System Software	1846	6.58	172	27.69	4.21	497	14.49	2.20	144	41.19	6.26	270	55.71	8.47
TEL-NW	Network/Internet Eqp & Components	654	2.33	48	7.73	3.32	225	6.56	2.81	39	11.16	4.79	113	23.31	10.00
SOF-HL	Health Services Software	653	2.33	46	7.41	3.18	99	2.89	1.24	42	12.01	5.16	25	5.16	2.22
SUB-SE	Semiconductor /Devices	899	3.20	62	9.98	3.12	317	9.24	2.88	45	12.87	4.02	184	37.96	11.85
SUB-ES	Electronic Subsystems	1260	4.49	79	12.72	2.83	301	8.78	1.95	60	17.16	3.82	96	19.81	4.41
TEL-NW-CH	Hubs	129	0.46	7	1.13	2.45	54	1.57	3.42	5	1.43	3.11	21	4.33	9.42
COM-AX	Computer Accessories /Components	621	2.21	26	4.19	1.89	156	4.55	2.06	20	5.72	2.58	44	9.08	4.10
ALL CorpTech Codes	all high-tech products	54238	193.33	3730	600.59	3.11	10043	292.86	1.51	2876	822.68	4.26	3443	710.35	3.67

Source: Q1 2004 CorpTech
Notes:
1. Route128/495 Region includes Middlesex County, Essex County, Norfolk County, and Suffolk County.
2. Silicon Valley Region includes Santa Clara County, San Mateo County, Santa Cruz County, Alameda County, and San Francisco County.
3. For consistency, the number of firms in SIC3661,3663 and 3669 is also based on CorpTech, that is, only include firms that produce high-tech products
4. 2002 population: United States: 280,540,330; Massachusetts: 6,210,578; Route 128/495 Region: 3,495,899; California: 34,292,871; Silicon Valley: 4,846,920
   Source: U.S. Census, http://www.census.gov/acs/www/Products/Profiles/Single/2002/ACS/US.htm
5. According to current Census definition, Boston belongs to Suffolk, and San Francisco belongs to San Francisco County.

TABLE 2
Semiconductor Devices (SUB-SE): Massachusetts vs. California

ST	Company Name	Empl.	Frmd	Ind.	Develop Consumer Products	Provide Components for Consumer Products	Manufacturing Facilities in Other Countries
CA	Atmel Corp.	7,550	1984	SUB	Y	Y	Europe
	Advanced Micro Devices, Inc.	12,146	1969	SUB	Y	Y	Asia, Europe
	Philips Semiconductors	6,650	1976	SUB	Y	Y	Asia, Europe
	Broadcom Corp.	2,700	1991	SUB	Y	Y	Asia
	Cypress Semiconductor Corp.	3,659	1982	SUB	N	Y	Asia
	Integrated Device Technology, Inc.	3,100	1980	SUB	N	Y	Asia
	Intel Corp.	78,000	1968	SUB	N	Y	Asia
	International Rectifier Corp.	5,900	1947	SUB	N	Y	Asia, Europe
	Linear Technology Corp.	2,600	1981	SUB	N	Y	Asia, Europe
	LSI Logic Corp.	5,300	1981	SUB	N	Y	Asia, Europe
	Maxim Integrated Products, Inc.	6,060	1983	SUB	N	Y	Asia, Europe
	National Semiconductor Corp.	10,100	1959	SUB	N	Y	Asia, Europe
	ChipPAC, Inc.	5,445	1997	SUB	Contract Manufacturer		Asia, Europe
	Sanmina-SCI Corp.	48,000	1980	SUB	Contract Manufacturer		Asia, Europe, South America, Australia
	Solectron Corp.	65,000	1977	SUB	Contract Manufacturer		Asia, Europe, South America, Australia
	Xilinx, Inc.	2,612	1984	SUB	N	N	Europe
	Sun Microsystems, Inc.	39,100	1982	COM	Y	Y	Europe
	Northrop Grumman Corp.	120,000	1939	DEF	N	N	None
	Synopsys, Inc.	3,700	1986	SOF	N	N	None
MA	Analog Devices, Inc.	8,600	1965	SUB	N	Y	Europe
	Skyworks Solutions, Inc.	4,200	1962	TEL	N	Y	Mexico
	Texas Instrument Inc./ Sensors and Controls	6,000	1952	TAM	N	Y	--
	M/A-COM, Inc.	3,325	1958	TEL	N	Mostly Not	None
	Mestek, Inc.	2,825	1898	ENR	N	Mostly Not	Canada
	Raytheon Company	76,000	1922	DEF	N	N	Canada, Europe

Source: Q1 2004 TechTrak / CorpTech and company web sites
Note: This table only lists companies that had over 2,500 employees as reported by the Q1 2004 TechTrak / CorpTech

TABLE 3
Data Network Switches: Massachusetts vs. California

Data Network Switches (TEL-NW-CS) Massachusetts vs. California			Massachusetts		California	
			Number of Firms	%	Number of Firms	%
Total Number of firms			21	100.0	66	100.0
Product portfolio	1	TEL-NW-CS plus other TEL products	16	76.2	51	77.3
	2	TEL-NW-CS plus COM products	2	9.5	15	22.7
	3	TEL-NW-CS plus SUB products	3	14.3	18	27.3
	4	TEL-NW-CS plus SOF products	9	42.9	22	33.3
	5	TEL-NW-CS plus TEL-NW-CB	4	19.0	24	36.4
	6	TEL-NW-CS plus TEL-NW-CH	2	9.5	17	25.8
	7	TEL-NW-CS plus TEL-CI-N	2	9.5	14	21.2
	8	TEL-NW-CS plus TEL-TD-S	2	9.5	18	27.3
	9	TEL-NW-CS plus SOF-CS-C	5	23.8	11	16.7
	10	TEL-NW-CS plus TEL-MX-O	0	0.0	10	15.2
Type of Products	11	Components and Parts*	5	23.8	33	50.0
	12	Carrier-class switches**	4	19.0	2	3.0
Diversity of Products	13	Less than 3 products (including TEL-NW-CS)	12	57.1	20	30.3
Size of Firms	14	<25	0	0	9	13.6
	15	25-500	16	76.2	31	47.0
	16	>500	2	9.5	22	33.3
	17	Unknown	3	14.3	4	6.1

Source: Q1 2004 TechTrak/CorpTech
Note:
*: Based on CorpTech company profile, the firm explicitly produced following products: microprocessors, chips, diodes, ICs, cables, chassis, cards, adapters, boards, interfaces and hard disks.
**: Based on CorpTech company profile, the firm explicitly defined its product as carrier-class/carrier-grade switches/routers.
Definition of CorpTech Product Codes:

TEL: Telecommunications and Internet
COM: Computer Hardware
SUB: Subassemblies and Components
SOF: Computer Software
TEL-NW-CB: Data Bridges
TEL-NW-CH: Hubs
TEL-CI-N: Network Interfaces
TEL-TD-S: Network Servers
SOF-CS-C: Communications Control Software
TEL-MX-O: Modems

Columns 6 and 7 indicate that no Massachusetts companies sell directly to final consumers and few are links in supply chains to companies that do sell to final consumers. This is consistent with the conclusion that Massachusetts high-tech companies tend to sell producer or capital goods used to make other goods and not components for consumer goods. Column 8 reinforces the theme. Most of the California component producers have facilities in Asia, while Massachusetts high-tech companies generally do not produce in Asia.

The results of a comparison of the product profiles of the 66 California and 21 Massachusetts companies that make data network switching gears (TEL-NW-CS) are presented in Table 3. Data network switches is a specialized branch of telecommunication equipment for which both Route 128 and Silicon Valley have high enterprise location quotients (see Table 1). It is a technology product category introduced by CorpTech in 1996 to account for the invention of packet-switching technologies and the development of the Internet.[19]

Lines 1-4 of the product portfolio comparison provide the other primary industry codes in which the data network switching gear makers are active. They reveal that Massachusetts data switch makers are more likely to also make software products and their California counterparts that are more likely to also make computer hardware, and sub-assembly and components. The next six lines (5-10) drill down to product codes to reveal that the California data switch makers are closely related to the personal computer (PC) industry and PC-related network equipment; in contrast Massachusetts data switch makers have a close connection with communication control software.

The second comparison in Table 3 (lines 11-12) shows the results of comparing the types of switches made in the two states. Whereas 50 percent of California companies that make network-switching gear also make components and parts, only 24 percent of Massachusetts companies do so.[20] In contrast, 19 percent of Massachusetts TEL-NW-CS companies make carrier-class switches, compared with only 3 percent of California companies. The third and fourth comparisons show that California data

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[19] CorpTech redefined its telecommunications codes to include TEL-NW (networks and components) as a separate sub-segment in 1991; the product code (third level of the classification hierarchy) TEL-NW-CS was introduced in 1996. Thus, CorpTech was able to add to its classification system to capture increasing specialization.

[20] A firm is categorized as a supplier of components and parts if its CorpTech company description and product profile refers explicitly to producing any of the following: microprocessors, chips, diodes, ICs, cables, chassis, cards, adapters, boards, interfaces, and hard disk drives. This includes products classified as, but not limited to, SUB-XX-XXX. Massachusetts firms in TEL-NW-CS usually design the whole "box" (system or sub-system) for the carriers, but do not supply components or circuit boards inside the box.

switch makers tend to produce a greater diversity of products and have more employees than those in Massachusetts.

Thus, firms in Silicon Valley, but not in Massachusetts, are good at equipment closely related to PCs and PC networks. Firms in Massachusetts are more competitive in designing equipment that requires more computing power, higher complexity, and better reliability; these are precisely the requirements for carrier-class communication equipment. The different patterns suggest an historical repeat: Silicon Valley firms are better in "micro-switches," while Massachusetts firms specialize in "mini-switches" or, in this case, "super-switches."

Figures 2-1 and 2-2 show the proportion of foreign headquartered companies in Massachusetts and California in 2003. Both states had about 8 percent of high-tech companies in CorpTech. In 4 of the technology categories, the ratio is between 2 and 3 times higher in Massachusetts than in California (chemicals, pharmaceuticals, advanced materials, and photonics). The number of foreign-headquartered firms in computer hardware in California is roughly double that of Massachusetts. For 7 of the technology categories the proportion is roughly the same in both states.[21]

These numbers are an indicator of regional core competence or "technology related externalities." Companies in specialized global technology bands can be assumed to have intimate knowledge of technology capabilities within their technology bands around the world. The fact that they invest in operations abroad is a market test of the attractiveness of a region in any particular technology category.

Figure 2-3 contrasts Massachusetts in 1997 and 2003 in terms of foreign-headquartered companies. The biggest growth areas are in photonics (from 10 to 16 percent) and pharmaceuticals (from under 11 to nearly 14-15 percent).

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[21] The numbers in the text refer to operating units of companies. An examination of employment data may change the results. Preliminary estimates suggest that employment figures mirror those of number of firms for the 4 technology categories in which Massachusetts has a location advantage in number of firms. However, the importance of a few large foreign headquartered firms in Massachusetts compared to California in factory automation, medical devices, energy, and computer software suggests that further research may reveal locational advantage in these technology sectors as well. For California, on the other hand, preliminary estimates of employment point to the possibility that a few big employers in environmental technologies may indicate a locational advantage not captured by number of operating units. We are presently conducting research on these matters.

FIGURE 2-1
2003 Foreign-owned companies in Massachusetts using CorpTech Taxonomy

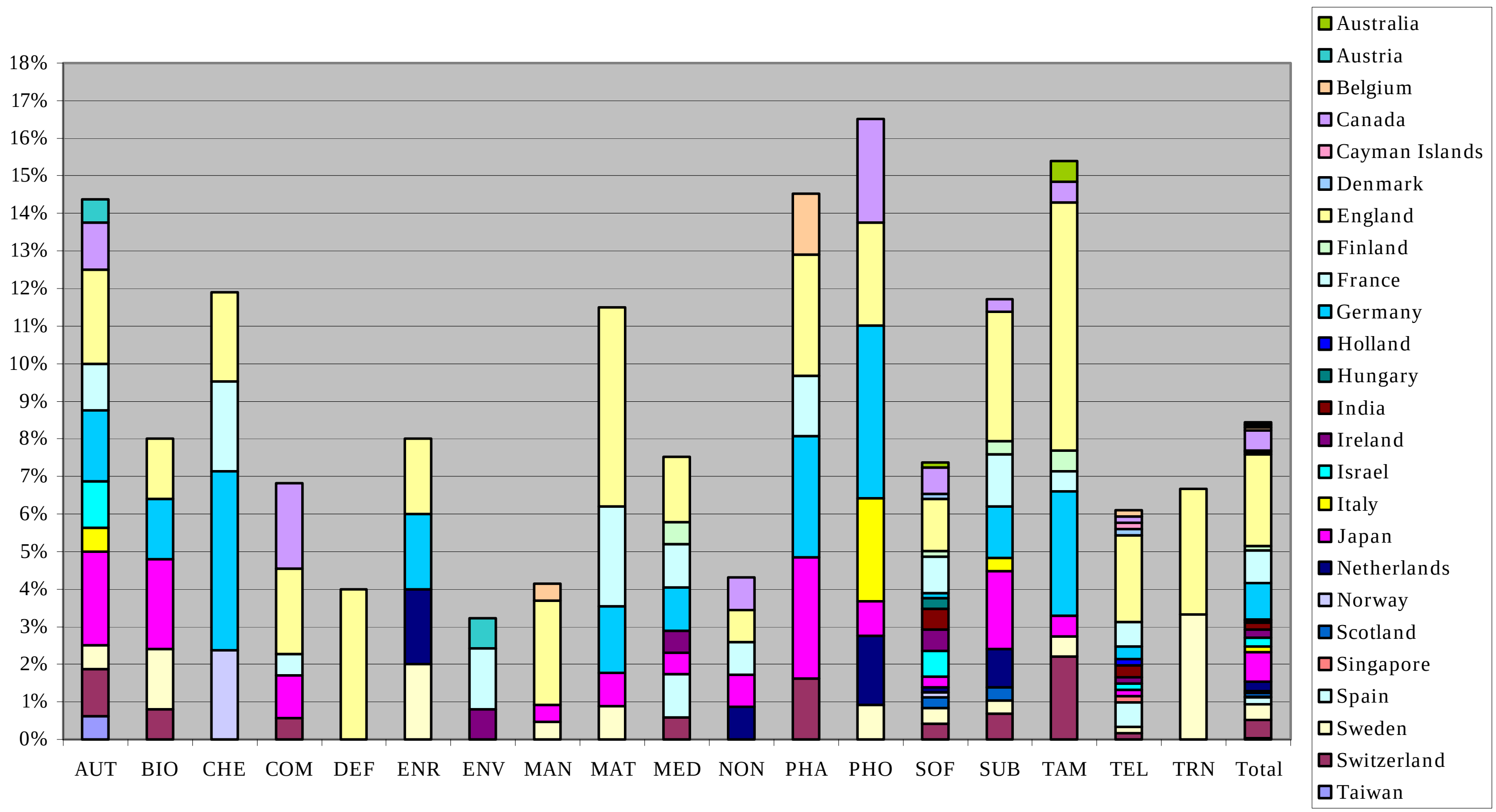

FIGURE 2-2
2003 Foreign Owned Companies in California using CorpTech Taxonomy

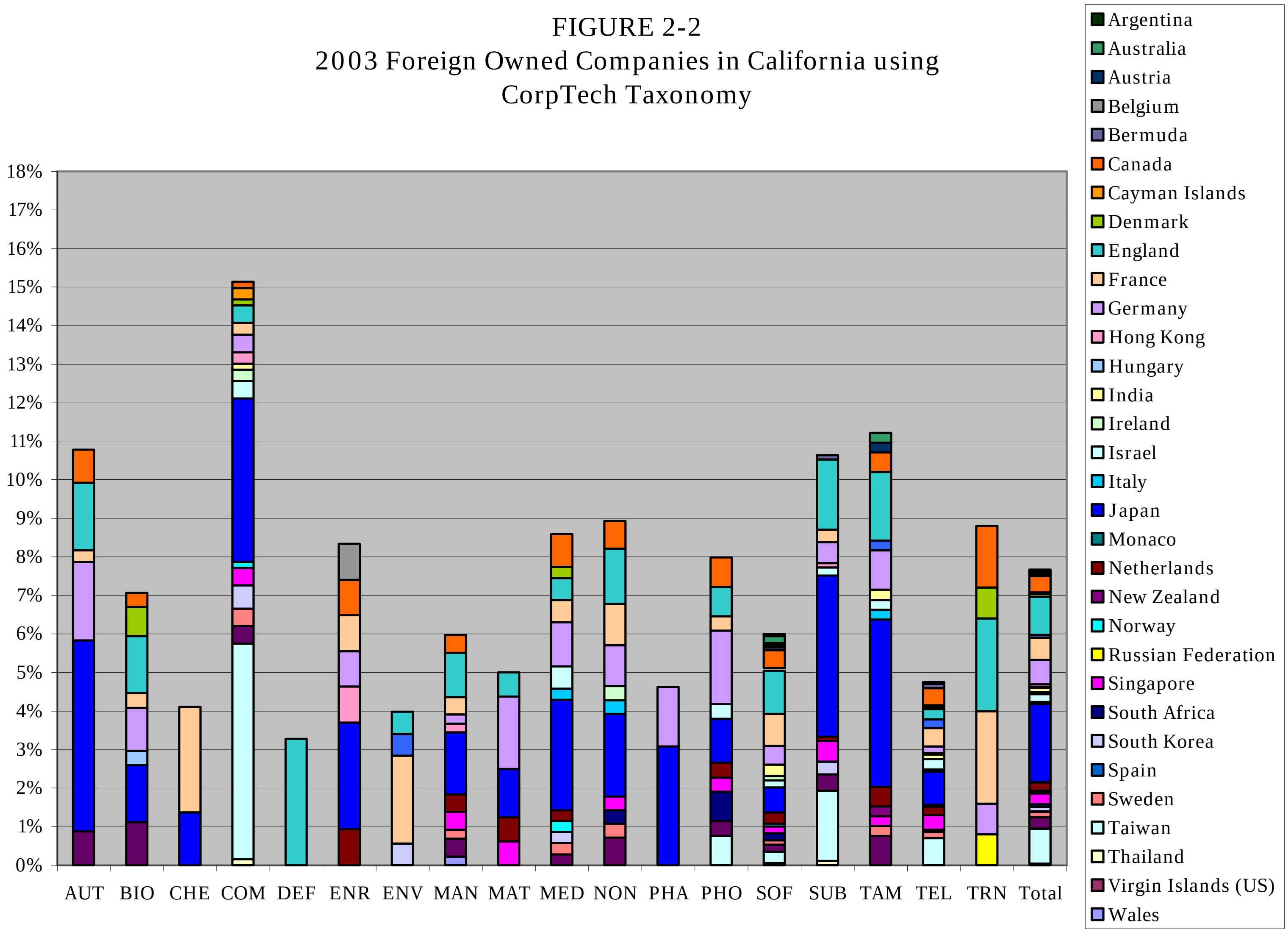

FIGURE 2-3

1997 Foreign-owned companies in Massachusetts using CorpTech Taxonomy

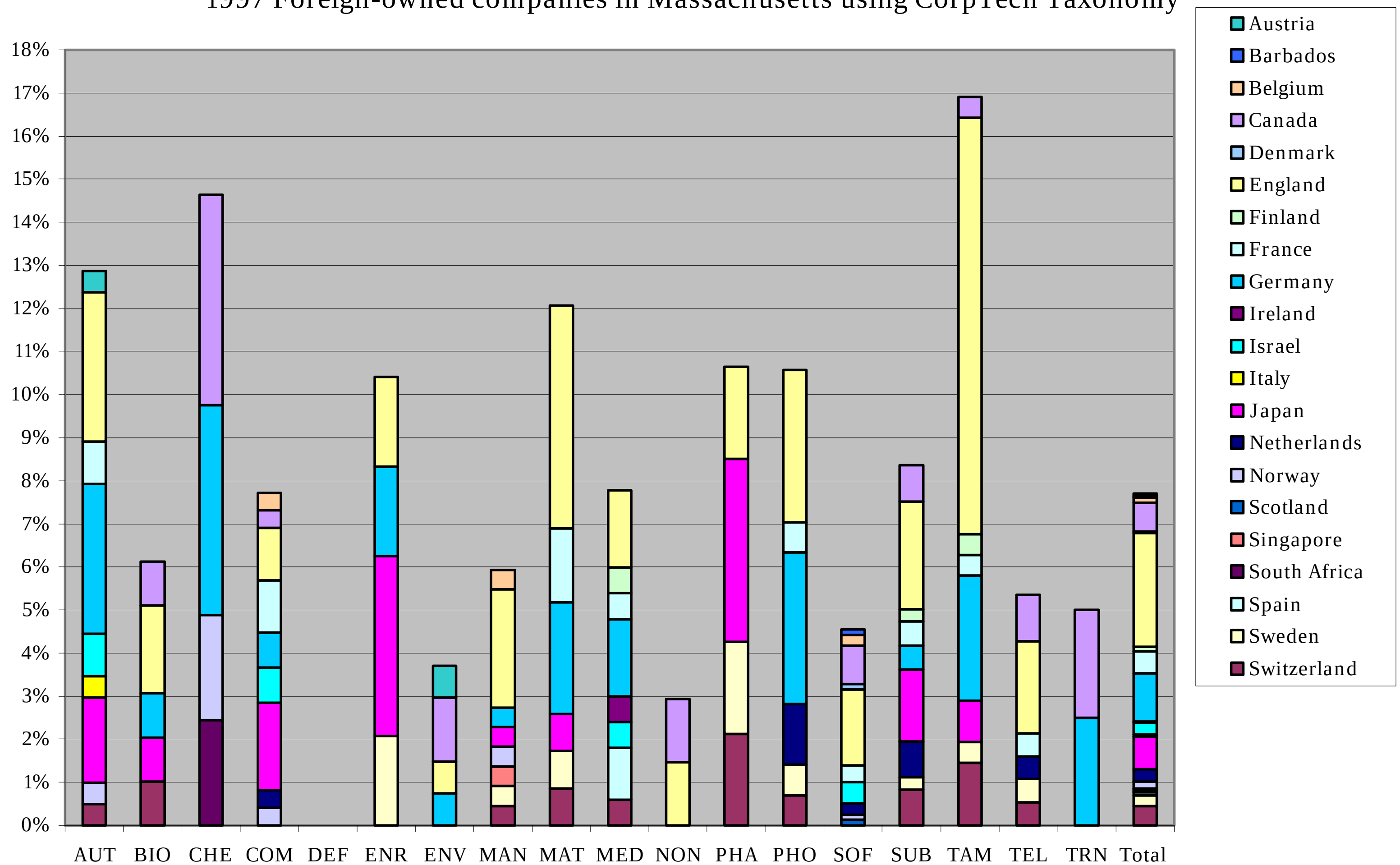

TABLE 4
Industrial Churns in Telecomm, Lowell-Chelmsford-Westford, 1997-2004

Company Name	Frmd	1997	1998	1999	2000	2001	2002	2003	2004
M/A-COM, Inc.	1958	SUB	SUB	SUB	SUB	SUB	SUB	3325	3325
ZipLink, LLC	1960	N/A	COM	COM	54	85	OoB		
Quallaby Corp.	1996	N/A	N/A	SOF	SOF	SOF	110	110	65
Lockheed Martin Microwave-FSI	1964	240	240	Acquired					
ITK International	1984	103	200	Acquired					
California Microwave/Microwave Networks	1987	100	100	Merged					
Microwave Radio Communications	1987	140	150	150	Merged				
Ascend Communications/Core Systems	1990	170	922	922	Acquired				
Tektronix, Inc. / BTT Division	1989	80	90	90	98	98	98	50-99	Merged
Optronics International Corp.	1968	190	80	80	100	MA			
e-Studio Live, Inc.	1971	N/A	N/A	N/A	18	55	52	MA	
AXIS Communications, Inc.	1984	MA			55	55	50	23	23
Davox Corp*.	1981	185	300	300	300	398	400	470	460
Biscom, Inc.	1986	42	50	70	60	66	60	60	60
Openpages, Inc.	1990	N/A	N/A	N/A	N/A	140	70	50	50
Intraplex, Inc.	1987	Unk	Unk	53	N/A	N/A	N/A	N/A	N/A
UNIFI Communications, Inc.	1990	MA	600	500	Unk	Unk	OoB		
Acacia Networks, Inc.	1995	N/A	N/A	60	60	60	Out of Contact		
OrderTrust, Inc.	1995	N/A	N/A	N/A	N/A	200	OoB		
Avici Systems, Inc.	1996	N/A	30	80	MA				
Integral Access, Inc.	1996	N/A	N/A	N/A	N/A	105	150	149	Unk
ArrowPoint Communications, Inc.	1997	Entry	N/A	40	80	Acquired			
Nortel Networks/Network Access	1997	Entry	N/A	66	unk	unk	250	250	Merged
Sonus Networks, Inc.	1997	Entry	N/A	N/A	115	115	745	497	371
Captivate Network, Inc.	1997	Entry	N/A	N/A	N/A	70	70	93	93
NetNumber, Inc.	1997	Entry	N/A	N/A	N/A	N/A	N/A	29	29
Convergent Networks, Inc.	1998		Entry	N/A	N/A	103	300	Unk	Unk
Sycamore Networks, Inc.*	1998		Entry	N/A	100	100	460	460	405
Brix Networks*	1999			Entry	N/A	30	100	50-99	50-99
Unisphere Networks, Inc.	1999			Entry	N/A	500	750	Acquired	
Crescent Networks	1999			Entry	N/A	Unk	66	14	OoB
Cratos Networks	1999			Entry	N/A	N/A	66	OoB	
WaterCove Networks, Inc.	2000				Entry	N/A	100	110	110
Storigen Systems, Inc.	2000				Entry	N/A	30	65	66
Narad Networks, Inc.	2000				Entry	N/A	125	149	50
Creative eTECH, Inc.	2000				Entry	N/A	140	140	149
SnowShore Networks, Inc.	2000				Entry	N/A	60	60	45

Source: Q1 1997,Q1 1998,Q1 1999, Q1 2000, Q1 2001, Q1 2002, Q1 2003, Q1 2004 CorpTech.

Notes: N/A: not listed in CorpTech. MA: other Massachusetts towns, suggesting that relocation took place. Unk: listed by CorpTech but employment unknown. Merged: merged of multiple units within a corporation. OoB: Out of Business.

*Davox Corp industry code changed from TEL to SOF (photonics) in 1998; Sycamore Networks industry code changed from TEL to PHO (photonics) in 2004, and Brix Networks industry code changed from TEL to SOF (computer software) in 2003.

Table 4 illustrates the concept of industrial churn using the example of telecommunications in the Lowell sub-region in Massachusetts. Three developments came together in the mid-1990s to change the dynamics of the region's telecommunications industry: the Telecommunications Act of 1996 opened the carrier-dominated retail end to competition from cable companies and Internet service providers; data-centric, packet-switching technology created new opportunities to drive down the cost of communication; and an "open-systems" focus and network model of business organization created opportunities for small, specialist companies to pursue market niches.

As shown in Table 4, at least 18 companies entered the industry with operating units in the Lowell sub-region between 1996 and 2000. Several grew rapidly including Nortel, Sonus Networks, Sycamore Networks, and Brix Networks.

Others that had operating units going back to the 1980s seized the opportunity and grew rapidly. Davox, founded in 1981, grew from 185 employees in 1997 to 470 in 2003. A provider of technology to the call center marketplace, Davox transformed itself from a provider of old-style outbound telephony into a CRM (customer relations management) provider with an integrated technology that embraces telephony, email, and the web. As a reflection of the company's capability development, its primary industry code changed from telecommunications to software and its major product codes to communications systems software (SOF-CS) and systems integration services (COM-SV-CC). Following an acquisition, Davox changed its name to Concerto Software in 2002.

Davox illustrates the new opportunities for increased specialization in a range of telecommunications-related technologies. Davox is also an example of a firm repositioned to seize new opportunities in telecommunications. Not all have primary industry codes in TEL. Netscout Systems, Inc., formed in 1984, as Frontier Software Development Inc., is a developer of local and wide area network monitoring services. Netscout's employment increased from 140 in 1998 to 355 in 2003.

Sycamore Networks Inc., founded in 1998, designs and manufactures intelligent fiber-optic network switches and the related software-intensive transport equipment for the communication backbone. Its primary industry code shifted from telecommunications (TEL) to photonics (PHO) in 2003.

Ascend Communications was perhaps the most spectacular crash during the period. Established as Cascade Communications in 1990, it was the first Lowell area company to respond to the emerging market for data-networking equipment. Cascade's employment grew from 28 in 1993 to 400 in 1996 when Ascend Communications of California acquired it. It grew to over 900 it was acquired by Lucent Technologies in 2000. The operating unit has since shut down.

The concept of industrial churn suggests a regional competitive advantage for both Route 128 and Silicon Valley: a capacity to rapidly reconfigure resources in response to new market opportunities and disruptive technological change. This example also sheds light on different forms of networking. California component producers are networked along supply chains in which the output decisions of all participants are coordinated. Such supply chains are the exception in Massachusetts where, as noted, the archetypal firm is not a component supplier but more likely a capital goods/services producer (equipment, instrument, device, and system software).

Network reconfigurations are sometimes conceptualized as spontaneous regroupings of skills across existing enterprises in an open-system.[22] New product development can involve inter-firm, virtual technology teams or "communities of practice."[23] However, the focus on sectoral, cluster, or district "churn" underlines the role of new firm creation as a vehicle for forming new teams to pursue innovative product, process, and technology ideas; it also points to the role of firm exits in replenishing the pool of engineers and other resources available to pursue next generation technologies.[24]

Implications and Findings

Production systems. Route 128 and Silicon Valley are considered America's two most successful high-tech regions. Yet, they have strikingly different production systems. Put simply, California has high volume production capabilities, which are rare in Massachusetts, as indicated by the near absence of contract manufacturers or component producers serving final consumer markets, directly or indirectly (see Table 2). Silicon Valley has enterprise location quotients many times that of Route 128 in electronic sub-systems (SUB-ES) and semiconductor devices (SUB-SE) as shown in Table 1. This is reflected in the California region's close integration with high volume operators in the Pacific Rim.

In contrast, Massachusetts' companies specialize in industrial equipment, instruments, and complex product systems. In fact, the historic lack of high volume production capability in New England was countered by 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. While Massachusetts lacks a heritage in

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[22] AnnaLee Saxenian, *Regional Advantage: Culture and Competition in Silicon Valley and Route 128* (Cambridge, Mass., 1994).

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

[24] The Massachusetts biotech cluster is an example in Michael Best, "The Geography of Systems Integration" in *The Business of Systems Integration*, ed. Andrea Prencipe, Andrew Davies, and Mike Hobday (New York, 2003), 205-232.

mass-production engineering and the associated deep craft skills, it is a leader in skills associated with systems engineering.[25] Today its strengths are in systems software, complex products, related industrial and engineering design services, in contrast to consumer applications such as PCs and computer games.

Thus, even in industries in which California and Massachusetts are leaders in the same SIC and NAICS sectors, and even in the same CorpTech product codes, such as data network switches (TEL-NW-CS), we find the production capabilities heritage tends to be respected and repeated in each region's successful companies. As shown in Table 3, one-half of Californian but fewer than one-quarter of Massachusetts' data network switch producers are component suppliers. Qualitative research reveals that Massachusetts companies supply most complex switching gear equipment to the major telecommunication carriers; whereas Silicon Valley companies are more likely to dominate the high volume, consumer-electronic end of the market such as hubs and routers for small business and homes.

The distinctive production capabilities of the two regions go some distance in explaining the "surprise" in both the emergence and rapid decline of minicomputers in Massachusetts. In the early days in the development of "real-time" digital computers, the design and production challenges were to develop and integrate a range of technologies (some emerging) and sub-systems. The region's strengths in complex product systems, including radar, feedback and control systems, software, and systems engineering were a match for the demanding design and production requirements of the emerging industry.[26]

For this reason the early minicomputer companies could get product development traction in the regional production system.

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[25] Many in Massachusetts, even many with technological backgrounds, resist the claim that mass production capability is extremely rare in Massachusetts. 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. See Michael Best, *The New Competition* (Cambridge, Mass., 1990), 147-161 and *The New Competitive Advantage*, 28-40, for comparisons of the two systems and references. 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 and the synchronization of cycle times. Each company may have good technical 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] See Kenneth Flamm, *Creating the Computer* (Washington D.C., 1988) and David Mindell, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics* (Baltimore, Md., 2002).

However, when the industry shifted from industrial to consumer electronics with the development of the PC, the region's production capabilities were a mismatch for the new, high-volume demands and the industry's location moved to Silicon Valley.

Technology Genealogy. Technology genealogy is important to industrial location. For example, Massachusetts has a long heritage in optics. Today this strength shows up in photonics companies that can collectively be described as a "self-sustaining cluster" or technology mini-cluster. This is not lost on photonics companies around the world: over 16 percent of Massachusetts's operating units in photonics are foreign-headquartered firms.

The development of optics-related capabilities in Massachusetts goes back to the early days of precision machining and the age of amateur astronomers.[27] American Optical Lens Company established in 1832 and likely the oldest optics company operating in Massachusetts, employs 40; The O. C. White Co., a manufacturer of microscopes was established in 1894 and still operates in Three Rivers, Massachusetts.[28]

While these firms are not industrial leaders today, they are beneficiaries of, and contributors to, the inter-generational stream of deep craft skills in optics/photonics that began with Massachusetts' leadership in precision-machining in the first decades of the nineteenth century. Today's successful companies and technology mini-clusters that operate in the derived technology trajectory may not be aware of their debt to the astronomer hobbyists who advanced lens-grinding capabilities in the region in pursuit of a glimpse into the more distant universe.[29]

In a recent study of the Lowell area, we found a large group of photonics, imaging, and optics companies that have market niches in specialist instrument-making. For example, McPherson, established in 1953, with 50 employees in 2004, supplies the world's science labs with optics tools for precision measuring instruments. Furthermore, McPherson's spectrographs fly in space rockets, and allow scientists to record and search out ancient events in the universe. Barr Associates, Inc.,

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[27] For more on the early links between machinists and the early optical industry in Massachusetts see Michael H. Best, *The New Competitive Advantage* (New York, 2001), 136.

[28] American Optical Lens employment figure as of September 2003 is from CorpTech, Second Quarter 2004. The O. C. White Co., with 18 employees in February 2004, makes industrial microscopes used in the electronics industry (CorpTech Q2, 2004).

[29] Perhaps the most famous hobbyist club in industrial history is the Homebrew Computer Club, a group of microcomputer enthusiasts founded in 1975. Members went on to found more than 20 computer companies. See Saxenian, *Regional Advantage*, 34 and Steven Levy, *Hackers: Heroes of the Computer Revolution* (Garden City, N.Y., 1984), 194. More on the astronomy hobbyists can be found at The American Precision Museum in Windsor, Vermont.

established in 1971 and with 350 employees in 2004, designs and manufactures infrared optical filters from less than 200 nanometers wavelength out to the far infrared (35 microns); few companies exist that can meet the challenge of optical filters to these wavelengths. The latest Hubble Telescope Servicing Mission has an instrument that contains 25 optical filters designed and manufactured by Barr Associates. Several other Lowell Area companies operate in optics, imaging, and X-ray technologies for various industrial sectors and government customers.[30] Although not included in optics or photonics, two other companies with operating units in the Lowell area are linked to the technology. Terradyne has been a leader in automated optical inspection technology and GenRad 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.[31]

Industrial Churn and Cluster Formation. The Massachusetts industrial system can respond rapidly when confronted with a surge in demand for new generations of complex product systems.[32] Figure 3 is a timeline that illustrates the speed with which a range of specialist companies in the telecommunication equipment making industry were created in Massachusetts. The trigger was a transition in the telecommunications

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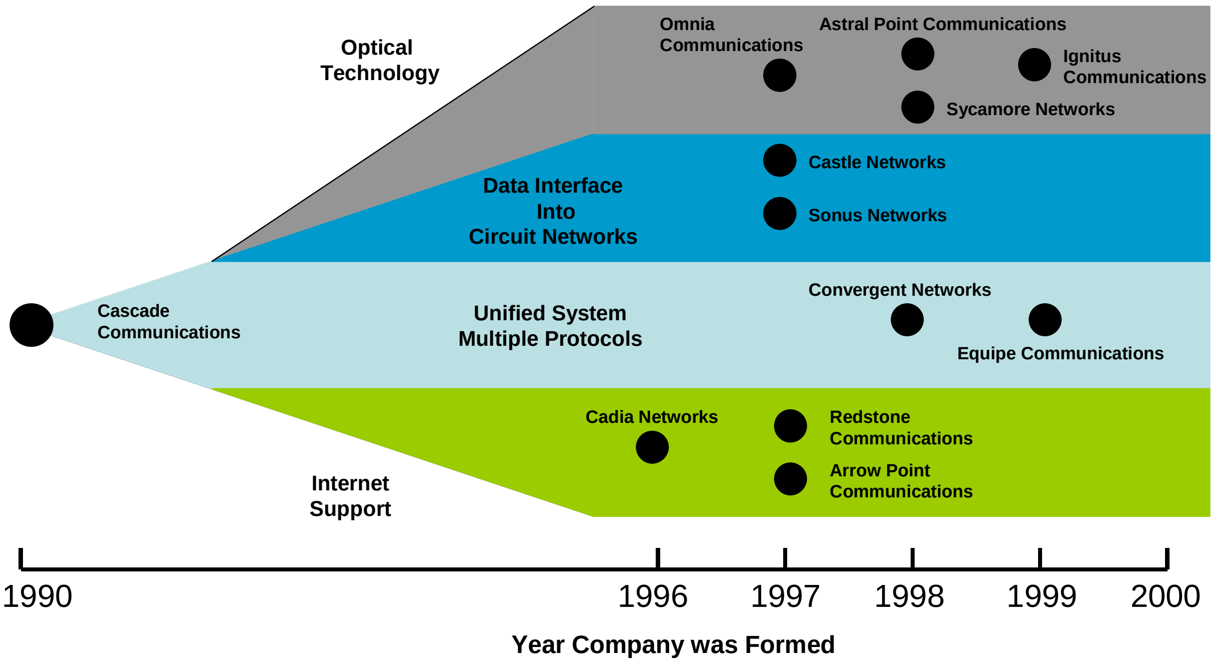
[30] During the Internet equipment-making boom, the Merrimack Valley region of Massachusetts was called "photonics valley" because of the concentration of firms that designed and supplied technology products for the backbone of fiber-optics networks. Other optics-related Lowell area firms include: Diamond USA, Inc., established in 1990, with 150 employees in 2004, manufactures fiber-optic systems, backplanes, devices, and cable assemblies for telecommunications, astronomy, and engineering businesses; Dielectric Sciences Inc., established 1970, with 35 employees in 2004, makes high-voltage cable assemblies for applications in high-energy physics, military radar, and industrial X-rays; Optelic US Inc., established 1985, with 70 employees in 2004, manufactures video magnification systems and hand magnifiers; and Cynosure, Inc., established 1991, with 150 employees in 2004, develops and manufactures medical lasers/optics. Less directly related, two Lowell area firms are leaders in the digital and image signal processing sector. Sky Computer products scan luggage and Mercury Computer Systems makes embedded computer systems for MRI (Magnetic Resonance Imaging) and CT (Computerized Tomography)-scan equipment.

[31] See Donald Sinclair, "The General Radio Company 1915-1965," http://www-2.cs.cmu.edu/~ram/electro/gr/GenRad_History.html.

[32] Route 128 and Silicon Valley are unrivaled in cluster formation capability. No region can match Massachusetts in sustained leadership in the development of new industrial sub-sectors going back to the establishment of the world's first machine-tool industry based on the principle of interchangeability. Both regions are leaders today in the creation of new clusters related to nanotechnology and the life sciences.

industry from a voice-centric, circuit switching to a data-centric, packet switching technology.

FIGURE 3
Product diversification of the Cascade "Family of Companies"



Both Massachusetts and California companies responded rapidly to the market opportunities created by the transition to a combined data- and voice-centric telecommunications system. However, not surprisingly, the new industry in Silicon Valley was built upon the region's previous strengths in semiconductor and microcomputer industries, while the success stories in Route128 evolved from the region's previous strengths in minicomputer and complex product systems.

Churn enhances the capacity of a regional system of enterprises to reconfigure in response to disruptive technological change.[33] An "open-system" model of industrial organization that facilitates network reconfigurations enhances churn.[34] 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 across the constituent enterprises. This specialization, in turn, fosters

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[33] This churn of enterprises counteracts the "innovator's dilemma" of single companies described by Clayton Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*, (Boston, 1997) but only if the region is populated by the "open-system" or focus and network business model.
[34] The concept of "open-systems" as both a design and organizational principle is developed in Best, *The New Competitive Advantage*.

technological innovation and the potential for yet newer enterprises and new configurations of enterprises. Such mutual specialization pressures are sources of new cluster formation.

Churn is both a blessing and a curse. On the blessing side it evokes a Schumpeterian "creative destruction" force that ushers in next generation technologies; on the curse side, it is a major contributor to economic instability. For example, Massachusetts has yet to recover from the collapse of the telecommunications equipment-making industry during the 2001-2003 recession. The transition from a business model of vertical integration to one of vertical specialization carried with it both a greater capacity for rapid response to an increase in market demand and a greater risk of rapid collapse because of a tendency to overshoot.

Jacobs' growth through differentiation distinguishes it from both classical approaches to the division of labor and modern approaches to the sources of regional specialization such as Michael Porter's. For Adam Smith, it was the division of labor that increased productivity and growth; from the capabilities perspective it is product innovation and the creation of new skills and capabilities that is crucial. Industrial growth comes from the process of creating new products, new work, and new skills.[35]

Thus, for both firms and regions growth is less about scaling up existing output and more about the processes of differentiation. This is consistent with the capabilities perspective, in that business success is about developing distinctive capabilities, not "once and for all," but as a consequence of the dynamic between productive capability and market opportunity. Firms and regions that fail to maintain a distinctive capability will lose out to competitors.

An organizational advantage of open-system industrial districts is that the pursuit of technological capabilities and market opportunities by diverse business enterprises involves endless reconfigurations of enterprise networks and enhancement of specialist capabilities. The reconfiguration of networks (associated with the death and birth of firms) is a means by which industrial districts are "self-organized."

Industrial Innovation and Open Systems. How has Massachusetts not only continued to conduct a large share of U.S. research, but to create new industries? Many see the links between R&D, product innovation, and industrial success as a linear process. They have focused attention, rightly, on new firm creation and spin-offs from university research. As important as this is and has been in Massachusetts, it also obscures pivotal processes underlying the region's success at reinventing itself industrially.

The "systems integration" capacity of a regional system of enterprises mediates between innovations in the lab and industrial

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[35] Michael Porter, "The Economic Performance of Regions," *Regional Studies* 37 (Aug./Oct. 2003): 549-78; Adam Smith, *An Inquiry into the Nature and Causes of the Wealth of Nations*, Glasgow Ed. (1776).

growth. Both are elements in "regional innovation systems." Here innovation involves differentiation of products and services and network reconfigurations; it may or may not involve investment in R&D to advance product development.

Network reconfigurations can involve spontaneous regroupings of skills across enterprises in an open-system.[36] New product development can involve inter-firm, virtual technology teams or "communities of practice."[37] 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.

Inter-firm networks are critical to the process. The capabilities theory analog is the open-system model of industrial organization in which networks are configured and reconfigured. Such networks are not limited to pre-existing or specific inter-firm networks, but to the potential for network reconfigurations. This requires the existence of a critical mass of firms with the complementary capabilities to make systems integration and re-integration possible.

Furthermore, the existence of "open-system" networks not only fosters reconfigurations and regroupings, collectively such networks form a regional industrial "infrastructure" that acts back on capability specialization within and among the constituent enterprises. This specialization, in turn, fosters new technological combinations and the potential for yet new enterprises and new configurations of enterprises. It can even involve "speciation" or the creation of new industrial sub-sectors.

In the case of innovation networks, innovation is a dynamic, iterative process. It evokes systems or connectionist theory: "the idea of representing a population of interacting agents as a network of nodes linked by connections."[38]

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[36] Saxenian, *Regional Advantage.*

[37] 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, W. Miller, M. Hancock, and H. Rowen (Stanford, Calif., 2000), 16-39.

[38] Waldorp, *Complexity*, 289. Along the same lines, Jacobs' account of cities as incubators of new firms and the sources of growth can be reinterpreted in terms of cities as sites of a critical mass of open networks (*Economy of Cities,* 145).

Industrial networks give "oomph" to innovation.[39] As noted, many regions have research-intensive universities and many universities can boast science-based spin-off high-tech companies but few can claim the impact on industrial growth associated with Route 128 and Silicon Valley.[40] For industrial growth to ensue, technology transfers and innovations generally need "oomph": a sizeable impact on firms and employment, directly and indirectly.

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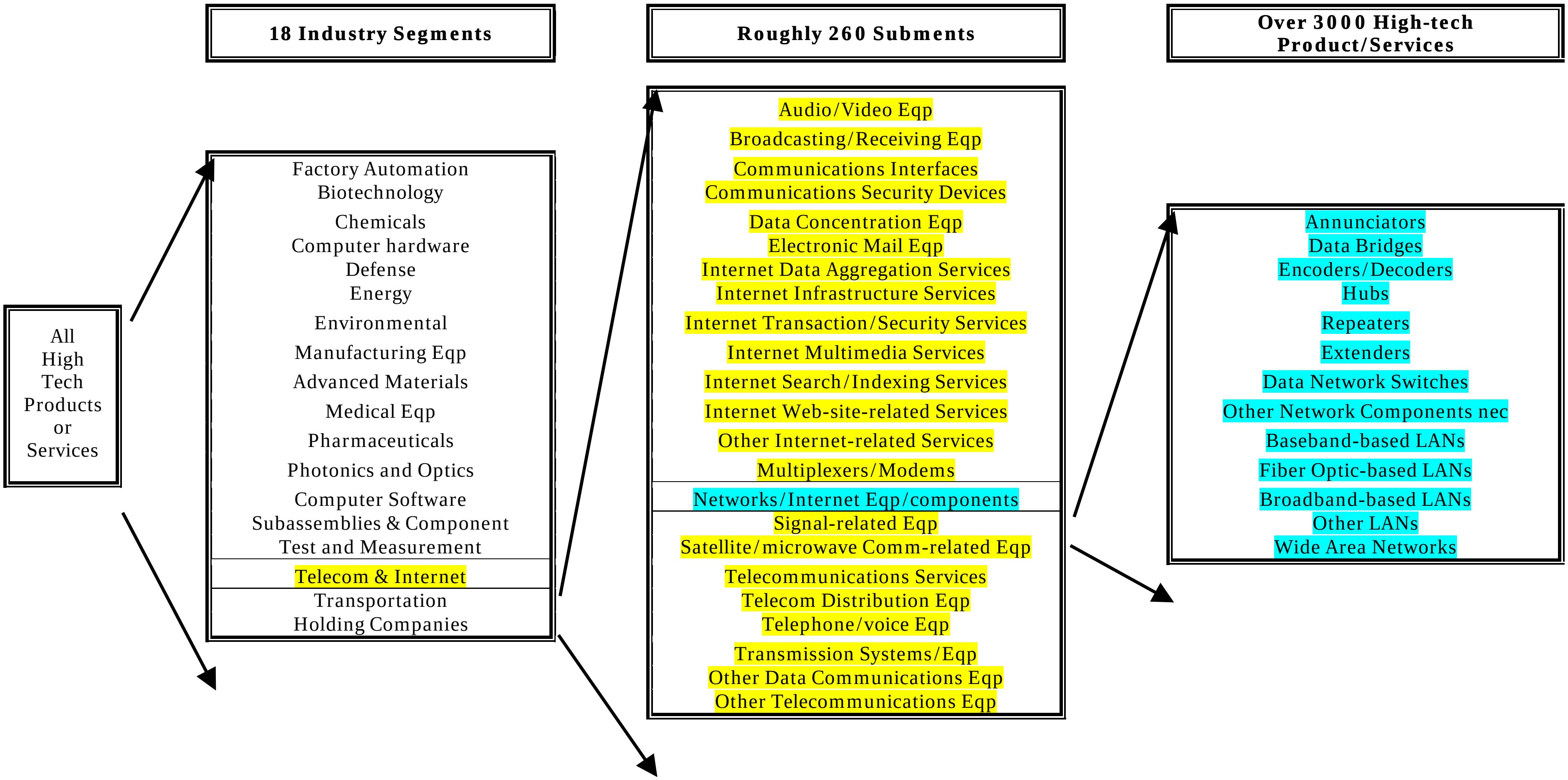
[39] Here we apply the term "oomph" as a criterion for the economic impact of innovation. Deirdre McCloskey introduced oomph as a criterion to judge economic research. Economic researchers, too often apply statistical significance/non-significance as the test of inquiry without regard to economic significance. Oomph is a test of quantitative effect. McCloskey writes, "economics has fallen for qualitative 'results' in 'theory' and significant/insignificant 'results' in 'empirical work.' You can see the similarity between the two. Both are looking for on/off findings that do not require any tiresome inquiry into How Much, how big is big, what is an important variable, How Much exactly is its oomph... Bad science—using qualitative theorems with no quantitative oomph and statistical significance also with no quantitative oomph—has driven out good." See Deirdre McCloskey, *The Secret Sins of Economics* (Chicago, 2003), p. 54.

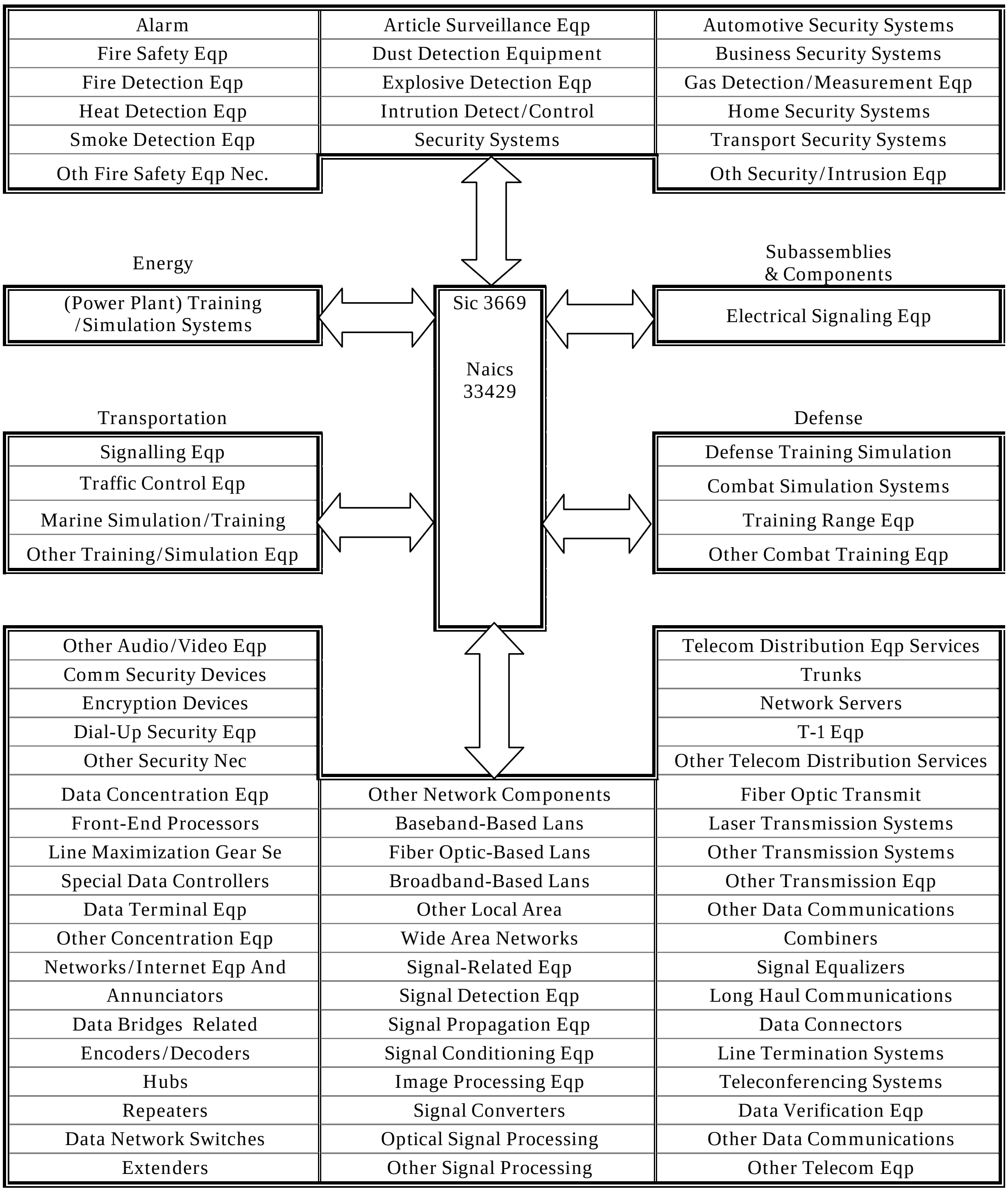
[40] The Whirlwind Project is one example of a university and industry relationship with oomph. The Whirlwind Project at MIT built the first "real-time" computer (beyond computation) fast enough to keep track of air traffic in 1949. Waldorp (*Complexity*, 154) describes its impact as extensive: "The system used magnetic core memory and interactive display screens to give birth to computer networks and paved the way for the use of computers in air-traffic control, industrial process control, ticket reservation systems and banking." Our claim is that oomph involved the combination of innovation and a regional production system with which it could interact.

Appendix A: CorpTech Classification System



Appendix B: Granularity of CorpTech Classification System

Test & Measurement



Telecommunications & Internet