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Locating Global Advantage

Industry Dynamics in the
International Economy

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Industry Creation and the New Geography of Innovation

The Case of Flat Panel Displays

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The growing knowledge-intensiveness of global economic activity demands new ways of thinking about industry, competition, and strategic management. This need presented itself to us dramatically in the research on the flat panel display (FPD) industry that we describe in this chapter. Our project started out as an investigation of an emerging high-technology industry that for many observers, including ourselves, represented a crisis of competitiveness for U.S. companies. The genesis of the thinking we present here occurred in our discovery that we were wrong. We had focused on the accumulation of physical plant and equipment, at the time concentrated in Japan, as the essential dynamic that defined new industry creation and its management challenges. In fact, the essential dynamics to be managed were global learning and knowledge creation processes that necessarily engaged an international community of companies.

Along with Japanese competitors, alliance partners, suppliers, and customers, U.S. companies with strong organizational capabilities in Japan played essential roles in commercializing the technology and creating the product application that sparked the FPD industry's high-volume takeoff. This technology is called thin-film-transistor liquid crystal display (TFT LCD, or TFT for short), and the product application was color displays for notebook computers. Color TFTs were first manufactured in a size, volume, and format suitable for use in notebook computers in the early 1990s. As the decade progressed, increasing workforce mobility, pervasive Internet use, and graphics-rich computer operating systems interacted to create explosive growth in demand for the color screens.

When a new technology commercializes first and draws significant capital investment in a particular country, as FPDs did in Japan, conventional wisdom assumes that local companies gain a potentially insurmountable lead over companies from elsewhere. But that did not hold true for TFTs and the flat panel display industry. At best, it represents a misleading assumption for strategy in new, knowledge-driven industries. The FPD industry emerged as a complex global network of relationships among companies and people. Each encompassed distinctive, complementary advantages and needs. Companies succeeded when their managers challenged assumptions traditionally used to formulate new industry strategies. Access to technology and market knowledge outweighed ownership and national location of manufacturing facilities as a determinant of business performance. Companies needed to reassess strategy processes that biased managers' thinking in favor of managing projects rather than people, building physical assets rather than creating knowledge assets, producing at home rather than learning abroad, and analyzing financial results rather than managing time.

During most of the twentieth century, a company on the brink of entering a new industry faced the moment of truth when management decided whether or not to commit funds to build a factory large enough to produce goods at minimum cost (Chandler 1962). Companies commercialized innovations by establishing manufacturing in their home countries. They projected their organizations outward to the rest of the world as market opportunities arose, and to seek minimum costs of capital, labor, and materials. Vertical and horizontal integration were prescribed internationalization modes to protect firm-specific knowledge from competitors and potential competitors by sharing it only within company boundaries. Similar reasoning motivated most international companies to center scientific leadership, research, and development at home.

As the high-volume FPD industry took off in the 1990s, many companies succeeded with strategies that seemed to invert these principles. Other companies tried to play by the rules and failed. When companies entering the FPD industry chose Japan over the United States to establish plants, they chose distance over proximity to the U.S. notebook suppliers that would become their biggest customers. Other countries besides Japan showed equal or greater promise as economic sources of materials. The companies invested before managers identified the high-volume product market opportunities that would bring the industry to critical mass. Some accepted relatively high costs of land, plant and equipment, labor and materials in order to locate at what appeared to be the geographic center of new industry developments. Many entered into codevelopment, production, and marketing alliances that required them to share vital, firm-specific knowledge, not only with suppliers and customers but

also with powerful international competitors. These successful companies moved decisively to create knowledge stakes in a new display functionality that offered myriad prospects in future product markets. They mobilized knowledge assets from around the world while centering their businesses in Japan, where the new industry was approaching critical mass. Their technologies and manufacturing processes had reached advanced stages of development when high-volume, mass product markets emerged.

The factors underlying the industry's emergence seem emblematic, in retrospect, of the "dynamics propelling globalization" that Kenney identified in his introductory chapter. Leading producers established their fabs in Japan, relying on advanced transport and communications to meet globally dispersed customers' requirements for physical product as well as continually evolving FPD functionalities. The industry's early geographic concentration in Japan arose and was reinforced because of the demands of knowledge creation in circumstances of extremely rapid market and technology evolution.

Yet it is important to acknowledge that the globalization dynamics that seem so powerfully reflected in this industry's early history did not initially unfold in a self-evident or deterministic fashion. Managers made a variety of strategic choices, with performance implications for their firms that varied from bankruptcy to market leadership. Successful firms created and then leveraged the dynamics, though not always with foreknowledge of the more difficult long-term implications for their own operations as these dynamics gathered force and assumed lives of their own. Unrelenting cost pressures, for example, emerged at least in part from the founding firms determined strategies to simultaneously advance the technology and at the same time introduce manufacturing economies. They were determined to create a mass market that could rapidly repay their enormous gambles on capital equipment. Geographic patterns of location emerged and were reinforced early in the industry's history because of firms' successful knowledge-creation strategies under conditions of rapid change. These patterns were recast when new firms in new countries bought existing knowledge to establish their own learning foundations for innovation. But not all senior managers of firms that tried to enter the industry saw or availed themselves of these cross-border learning opportunities. Some saw dangerous dependence rather than fruitful interdependence, limited their global ties, and as a consequence made enormous losses.

In this chapter, we explain how U.S. companies that succeeded in becoming leaders in the flat panel display industry adopted strategies that allowed managers and engineers to engage in critical knowledge-creation processes at the geographic center of the industry. Successful U.S. companies located the headquarters for their display businesses in Japan and leveraged their companies'

global technology and market resources to build their presence in the industry. U.S. companies that failed adopted strategies that focused on domestic collaboration among FPD fabrication equipment and materials makers to create a new, U.S.-origin toolset for FPD production on U.S. soil. The U.S. government policies that encouraged these strategies evoke Duguid's distinction (in this volume) between "physiocratic" and "new economy" as a way of characterizing policy-makers' mindsets. U.S. policy-makers focused on trade in goods, while the industry's emergence was fundamentally driven by trade in knowledge. We focus in this chapter on the firms that successfully exploited this reality. Our book *Managing New Industry Creation* (Murtha, Lenway, and Hart 2001) offers a more complete FPD industry history, along with general frameworks for strategy derived from the top performers' experiences.

We argue here that U.S. companies needed to leverage organizational capabilities and physical locations in Japan in order to create the knowledge necessary to build globally competitive manufacturing facilities. After large-format TFT LCDs commercialized in the early 1990s, FPD manufacturing equipment and process technology evolved across multiple generations at a pace that, up to that time, had never been seen in high-technology industries. Managing transitions to new generations required engineers and equipment operators who could draw on their experience and understanding of previous generations to solve problems in bringing new manufacturing facilities on line. This reservoir of experience was critical to improving yields, which drove manufacturing costs down and helped to reduce prices to increase consumption. The pace and specific configuration of each generational shift emerged from intimate, first-hand interactions among people representing FPD manufacturers, equipment providers, and materials producers. Physical proximity played a critical role. The pace of generational shifts increased after IBM introduced its first portable computer with a color display, the ThinkPad, which triggered an explosion of demand for TFT LCDs. After the ThinkPad's introduction, TFT production also started up in Korea, where companies began their own knowledge creation processes after first acquiring and learning to use earlier generations of process technology and manufacturing equipment.

The LCD's Beginnings

On May 28, 1968, at RCA's Rockefeller Center headquarters in New York City, company officials held a press conference to unveil a "very crude prototype" of a liquid crystal display. Many people present—both media and company representatives—hoped the new technology would soon replace the cathode ray tube (CRT) as the world's dominant image-engine and transfigure into the first flat TV. This tiny TV of the future was the first flat panel display presented to the

general public. It used the new technology to show a black-and-white image of two moving lines.¹ RCA engineers demonstrated other LCD applications as well, including an electronic clock that was widely shown in print and on TV news programs around the world.

The demonstration culminated years of work at RCA's David Sarnoff Research Center. Liquid crystals were, at the time, a relatively obscure family of materials. Richard Williams had demonstrated at Sarnoff around 1960 that a liquid crystal substance in its transparent state turns opaque, and scatters (or reflects) light instead of transmitting it, when charged with an electric current (Johnstone 1999: 96). In 1964, George Heilmeier led some of the first experiments that harnessed this property to create an image-capable display, fueling the research program that ultimately led to RCA's announcement. Sarnoff's engineers discovered liquid crystal material that retained its crystalline properties over a wide temperature range, and they used transparent electrodes and a polarizer to electrically control the liquid crystal's optical properties. They called their method "dynamic scattering." With the dynamic scattering breakthrough, commercial release of the first flat television entered the range of feasibility, the company asserted in response to journalists' inquiries.² But many technical problems remained to be resolved before flat TV could become a reality. Most serious among these, researchers needed to find cost-effective, manufacturable means to electronically address the complex mosaic of tiny picture elements, or pixels, that would be needed to display a well-defined, moving image.

Within a few years, however, RCA began to diversify away from consumer electronics. After RCA's visionary founder, David Sarnoff, died in 1971, CRT replacement fell off of the agenda for the corporate managers who succeeded him. In 1973, the company made a brief foray into LCD manufacturing for point-of-purchase displays and later watches. But within a few months of starting operations in Somerville, New Jersey, RCA sold the plant to Timex, the watch company (see Brinkley 1997: 51; Johnstone 1999: 35, 102–5; and Harrison 1973). RCA's 1975 annual report made no mention of its LCD program, which had disappeared some time the previous year.

In Japan, engineers at Sharp Corporation had watched news reports of the RCA press conference with interest. Sharp set out promptly to incorporate the new technology, complete with warts, into a commercial product: the hand-held calculator. The company, then known as Hayakawa Electric, had pioneered the business in 1964 with the Sharp Compet, the first fully electronic calculator to be manufactured at commercial scale.¹

Sharp engineers initially asked RCA to manufacture LCDs for their calculator. RCA's management decided that the technology was not sufficiently mature

to manufacture. Instead, RCA licensed its dynamic scattering LCD technology to Sharp in 1970. In April 1973, Sharp introduced the EL-805, the first calculator with an LCD display. The LCD calculator was followed within a few months by the first LCD watch, introduced by Seiko.

Both Sharp and Seiko began early to seek outside customers for their displays. The companies found that engagement with outside customers not only brought in revenue but also diversified and invigorated their R&D efforts. The companies continued to upgrade their FPD technology to meet their own future product needs and to meet customers' needs and specifications. Apple Computer, in particular, acted as an early, influential Sharp customer for its pioneering notebook and personal digital assistant. Its graphical user interface operating system preceded Microsoft Windows by a number of years. The visual demands of Apple's operating system added great impetus to FPD producers' initial quests for color, high resolution, size, and smooth video motion.

As the industry's potential grew increasingly evident from the middle 1980s up until the notebook computers takeoff in the early 1990s, joint efforts among manufacturers, equipment suppliers, and materials manufacturers were needed to enable the transition to high-volume production of the largest, most advanced displays. Sharp was again involved, along with Toshiba and IBM as FPD producers, and Applied Materials and Corning in equipment and materials. Several of these companies competed with each other in related fields. Cooperative relationships with downstream system integrators such as Apple Computer and Compaq played a role, even as some FPD producers began to compete with them for notebook market share. Without these cooperative relationships, the high-volume FPD industry would have emerged eventually, but not as rapidly as it did.

IBM Japan Wins a Mandate

In the mid-1980s, IBM assembled a number of task forces to examine alternative FPD technologies and their prospects for replacing the CRT. IBM had for many years researched and manufactured large, flat, black and white Plasma Display Panels (PDPs) for industrial use (primarily financial markets), and sourced large quantities of CRTs to incorporate in its popular line of computer monitors. The task forces identified color reproduction as a critical display characteristic for users, and TFT LCDs as the technology with the most promising future. The cost of developing color PDPs appeared prohibitive at the time, although the technology has since surmounted that obstacle to gain status as a leading contender for dominance in large, flat home televisions (see Murtha, Lenway, and Hart 2001: 46-48, 71-77).

IBM senior managers decided to locate a new TFT LCD development project in Japan with IBM Japan in the leadership role. The project was established as an alliance with Toshiba. Both companies contributed capital, people, and facilities for the project, which set a goal to develop the largest TFT LCD color prototype possible, as quickly as possible. The researchers on the project team received support from experienced LCD researchers at IBM's Thomas Watson Laboratories in Yorktown Heights, New York, and Toshiba's corporate R&D staffs. The companies agreed to each host the project for one year in their respective facilities in Japan, starting at Toshiba, where a rudimentary R&D line was to be erected as soon as possible. At the end of the project, each company would be free to independently pursue further research or manufacturing plans. The contract was officially signed and work began on August 1, 1986. Sharp, which was ramping up high-volume production of a 3-inch color TFT display at the time, also decided to vault ahead to something much larger.

By summer 1988, both Sharp and IBM/Toshiba had developed TFT LCD prototypes measuring around 14 inches diagonally, demonstrating a potential for flat video reproduction that had seemed only remotely conceivable in the time immediately following RCA's LCD announcement twenty years earlier. Neither company paused for long to debate the question of which had arrived first at the starting line in the race to commercialize large-format TFTs. Both had arrived at a turning point that offered the sobering opportunity to place far greater resources at risk building high-volume facilities and proving a high-volume production process. Managers and engineers in all three companies knew that fashioning large prototypes individually represented R&D achievements, but building them in quantity represented a serious manufacturing challenge.

The 14-inch color TFT LCD prototype developed by the IBM/Toshiba team was presented to IBM's top management in 1988 at a meeting in Japan. Web Howard, a senior IBM physicist, made the case to IBM's top management that the portable personal computer market would grow sufficiently large to warrant high-volume TFT LCD production. He predicted that users would be willing to pay up to five times more for a TFT LCD than a CRT monitor because "they provided a new platform for taking work anywhere" (Howard 1996).

Managing Intra-industry Interdependence

According to a respected former industry analyst in Japan, "an atmosphere of euphoria" prevailed as prospective TFT LCD manufacturers faced production investment decisions in 1989. Other companies besides Sharp, IBM, and Toshiba—most notably NEC—had pursued TFT research for large-format color TFT LCD displays for many years. The 14-inch prototypes suddenly raised

the stakes. The announcements altered perceptions of what could be achieved in the short term and thereby changed assessments of the pace at which commercialization of large-format TFTs would proceed. Published estimates of industry potential mushroomed to \$10 billion for 1995 and \$40 billion in 2000.⁵ FPD industry possibilities received more mass media attention than RCA's original 1968 LCD announcement. TFT production planning appears to have moved from the back burner to the fast track in a number of firms.

Nearly one year after the IBM/Toshiba prototype announcement, on August 30, 1989, the two companies announced their agreement to form a manufacturing alliance, Display Technologies, Inc. (DTI). The alliance was structured as a 50–50 percent joint venture between Toshiba and IBM Japan. The partners initially capitalized DTI at about \$140 million, earmarking \$105 million for a high-volume TFT LCD fabrication facility. DTI's headquarters and first fab would be located in Himeji City, next to one of Toshiba's manufacturing facilities. DTI officially started up on November 1, 1989. Sharp management also decided sometime between 1988 and 1989 to go ahead with large-format color TFT manufacturing. Both companies announced plans to initiate production on Generation 1 lines in fall 1991.

At Toshiba and Sharp, managers anticipated that the new large-format color TFT LCDs would sell at high volume only if the market was globalized at the instant of its creation. Sharp prospected for global customers such as the U.S. computer makers Apple and Compaq. Toshiba's managers did the same, but also concluded that collaboration with IBM would help globalize the Japanese company's insular management culture. Tsuyoshi Kawanishi, a senior Toshiba executive who was instrumental in forming the DTI alliance, anticipated that the United States would play a big role in the market for final goods in any long-term TFT LCD scenario. His experience with the semiconductor trade wars of the mid-1980s alerted him to the possibility that similar tensions could arise with the U.S. government over concentration of FPD manufacturing in Japan. He hoped that establishing TFT manufacturing as a joint venture with a U.S. company would help defuse the impact on the business of any such development.⁶

Creating a high-volume manufacturing process would also require close partnerships with equipment and materials suppliers who could contribute specialized expertise, technologies, and research muscle. Many potential suppliers, such as Canon, Nikon, Toray, and Anelva, were Japanese, and they enjoyed long-established relationships with the companies considering TFT manufacturing. Several U.S. electronics equipment and materials suppliers with operations in Japan were considering the opportunities that mass production of large TFTs might offer. Toshiba approached Applied Materials to design and

manufacture chemical vapor deposition (CVD) equipment, although the companies did not reach agreement in time to equip the first generation of TFT LCD fabrication facilities. Corning had played an indispensable role in TFT development from the beginning, having followed up on unanticipated small orders for its specialty glasses from large Japanese corporate electronics laboratories in the early 1980s. By the middle of the decade, it was already well established as the leader in manufacturing specialty glass for smaller TFTs.

In September 1989 the business press in Japan heralded optimistic projections for large format TFT LCD production. Beginning in April 1991, Toshiba and IBM partners expected DTI to begin a ramp-up that would quickly bring production to a rate sufficient to produce 200,000 TFT LCDs a year, or roughly 16,000 displays per month, with an increase to 1,000,000 displays per year in 1994.⁹ In early October 1989, Sharp announced a less ambitious target of 3,300 to 5,500 units per month for its planned autumn 1991 production startup.¹⁰ Several months later, NEC managers announced that it would also jump into the market in 1990. In the months prior to the 1991 production startups, the consensus view among the pioneering manufacturers held that by 1995 large TFT LCD screens would reach price levels attractive in the mass market, less than \$500.¹¹

Yield Wars

On May 15, 1991, DTI announced that production had started up earlier in the month, with the first TFT LCDs scheduled for shipment within a week or two.¹² But the ramp-up did not go smoothly. DTI engineering director, Hidenori Akiyoshi commented, "We actually started from nothing. Nobody, us included, had any experience with large-format TFT LCD production. Although a test production run had been carried out by Toshiba's laboratory, a lot of unexpected problems were waiting as we ramped up. When we started production, the overall line yield was far below 10 percent, primarily due to equipment problems (West and Bowen 1998: 6)."

Corning had anticipated the movement toward large-format TFT LCD production with its early 1988 decision to build fusion glass production facilities in Shizuoka. Just before the first high-volume plants ramped up in Japan, Corning established its glass substrate business as Corning K.K., a distinct, global business unit with authority and accountability centered in Japan, headed by President Satoshi Furuyama. The organizational processes that led to these decisions, which anticipated TFT demand by more than three years, proved fateful for Corning's market position. When the new Sharp and DTI facilities initiated production in 1991, they required a sufficient supply of substrates to

operate at full capacity, despite low yields. Even if most production ended up as waste, the rate of process learning to increase yields varied directly with throughput. As IBM's Bob Wisnieff said, "It takes an awful lot of glass flowing through a line, really just acting as a pipe cleaner."¹³

In September 1991 yields at DTI reportedly hovered around 8 percent.¹⁴ In other words, fewer than one in ten displays coming off the new line could actually be sold. Other companies were experiencing similar frustrations. By the March 31, 1992, conclusion of Japan's 1991 fiscal year, DTI had shipped a total of 30,000 displays, or about 4,200 per month. But as Sakae Arai, senior manager of LCD marketing at Toshiba said, finding working units to ship "was like picking through the garbage."¹⁵ At costs running \$2,000 to \$3,000 per working display, the manufacturers were shipping money out the doors.

The yield problems emerged because the earliest high-volume manufacturing equipment and process generated particle contamination at a rate far greater than anyone had anticipated. The process developers had refined the methods and equipment for creating thin film transistors—particularly large-area chemical vapor deposition (CVD)—from amorphous silicon technology perfected for solar energy panels.¹⁶ Solar energy panel performance is indifferent to particles introduced in the manufacturing process. Not so with TFT LCDs, where a single microscopic particle can cause pinhole dropouts or color variations on the final product. Improved CVD equipment emerged as one of the most important challenges among many in the struggle to improve yields."

After much persuasion, Toshiba and Sharp convinced Applied Materials of Santa Clara, California, to leverage its semiconductor equipment-making experience to develop a CVD tool for second-generation TFT LCD fabs. The company formed a new unit, called Applied Display Technologies (ADT), which developed the new tool. After forming an alliance with Komatsu, Ltd., the renamed AKT established its worldwide headquarters in Kobe, Japan, with Applied Materials Japan chairman Tetsuo Iwasaki as president. The company delivered its first product, the AKT-1600, in Mid-1994. The new tool's contribution to yield enhancement helped span a productivity gap that impaired the TFT LCD's promise as the first FPD technology to challenge the CRT for display market dominance. It rapidly established AKT as the leading force in CVD. Since reverting to 100 percent Applied Materials control in 1998, AKT has retained this leadership as well as its U.S. manufacturing base.

The problems, however, could not be attributed to any one piece of equipment. DTI's Akiyoshi explained that yields suffered from electrostatic charge buildup, contaminants introduced in CVD operations and on panel carriers, glass panels chipping or cracking, inferior seals in panel assembly, and out-of-spec materials. "Unless we change the current production concept," com-

TABLE 7.1
Main Commercial Generations of Color TFT LCD Substrates

Generation	Typical substrate size	Optimized for display size (qty.)	Earliest adoption: startup dates, adopters
0	270 x 200 mm	8.4-inch (2)	1987 Sharp
1	300 x 350 mm	9.4-inch	3rd Quarter, 1990 NEC
	300 x 400 mm	10.4-inch (2)	2nd Quarter, 1991 DTI
2	320 x 400 mm	8.4-inch (4)	3rd Quarter, 1991 Sharp
	360 x 465 mm	9.5-inch (4)	2nd Quarter, 1994 Sharp
2a	360 x 465 mm	10.4-inch (4)	2nd Quarter, 1994 DTI
2.5	400 x 500 mm	11.3-inch (4)	3rd Quarter, 1995 Sharp
3	550 x 650 mm	12.1-inch (6)	3rd and 4th Quarters, 1995 Sharp, DTI
3.25	600 x 720 mm	13.3-inch (6)	1st Quarter, 1998 Samsung
3.5	650 x 830 mm	17.0-inch (4)	3rd Quarter, 1997 Hitachi
		15.0-inch (6)	3rd Quarter 2000 Samsung
3.7	730 x 920 mm	14.1-inch (9)	

Sources: Business press and interview materials.

mented Kouichi Suzuki, general manager of Toshiba's LCD division, "we won't be able to cut prices" to achieve mass-market penetration."

Substrate size increases contributed to enhanced productivity, but created a new set of challenges as companies needed to qualify and ramp up new generations of manufacturing equipment for each new size. The evolution from generation to generation unfolded at an unprecedented pace. AKT top management has suggested that the rate of change in FPD technology between 1990 and 2000 exceeded the rate of change in semiconductor technology from the mid-1970s to 2000 by a factor of eighteen, measured according to substrate area (Law 2000). Another way of looking at expanding substrate sizes (see Table 7.1) suggests that TFT LCD makers endured at least five generational changes in half the time the semiconductor industry endured the same number of transitions.²⁰

The Generation 1 fabs had cost around \$150 million in plant and equipment. Within months, legend had it, mountains of broken glass from unacceptable products piled up behind the fabs of the pioneering manufacturers, who were

also piling up materials costs for process creation and refinement that closely approximated their investments in capital equipment. Discussions with equipment and materials manufacturers about a next generation of high-volume process technology started even before the Generation 1 fabs went on line. Success in the second generation of production equipment, however, would depend on the companies' abilities to create and retain knowledge in waging up the first.

Increasing yield figures represented the most visible measure of knowledge creation and accumulation. In effect, each company's fab acted as a laboratory, seeking successful outcomes to experiments that would shape the next and subsequent generations of production technology. DTI president Toru Shima described the problem: "In order to take advantage of the best materials and equipment, we need first to deal with internal barriers to high yields."²¹

Invested in a fixed stock of capital equipment, managers in each company soon acknowledged that successful yield management would depend more than anything else on the people involved. Companies could not address this dependence solely by promoting learning, as a company might do, for example, by improving operator training. Training assumes an existing body of knowledge. The process was unsettled, and not working very well in any case. The scientists, engineers, and operators were identifying problems and inventing critical process refinements in real time, as they did their work. The companies faced a challenge in finding ways to enhance these individualized and team-based knowledge creation processes. They also needed to find ways to generalize the resulting knowledge, diffuse it within their organizations, and channel it into creating the next generation.

NEC's engineers spent months working in the fab with counterparts from equipment and materials manufacturers, drawing comparisons that might help explain why any one machine should achieve different yields from another of the same type. Methodologies were invented to study operators' movements, in hope of identifying specific behaviors that might contribute to performance differences among different individuals using the same machine. To facilitate this monitoring, operators attached bar codes to each other, each piece of glass, and each machine, and submitted one and all to computer monitoring. Draconian as these measures may have appeared at the time, the operators discovered surprising sources of particle pollution in otherwise mundane behavior. Shigehiko Satoh, engineering manager at NEC's LCD fab in Izumi, expressed his hope to a touring visitor that cleanroom operators would refrain from sitting down, as doing so would release a cloud of invisible particles sufficient to destroy thousands of dollars worth of products.²² By late fall of 1991, as other companies struggled to push yields to 25 percent, NEC claimed industry lead-

ership by announcing that it had achieved 50 percent. Some months later in mid-April 1992, DTI had reportedly reached yields of about 40 percent, while NEC claimed yields well above 50 percent, on the way to 80 percent.

The Face of a New Machine

In November 1992, IBM Personal Computer Company (PCC) introduced a product line that would transform skeptics' views of the company's TFT program from high-risk gamble to prescient vision. Model 700C, the first in a long line of ThinkPad notebook computers, attracted immediate attention not only for its computing functionality but also as a marvel of industrial design. The DTI 10.4-inch color TFT LCD, the largest, brightest ever available, transformed 700C owners into targets of their coworkers' envy. The unit also incorporated a small trackpoint embedded within the center of its full-size keyboard to perform cursor functions. The 700C's computing capabilities were built around an Intel 80486 processor and 120 Mb hard drive. The 10.4-inch display offered up to 50 percent more screen space than other color TFT LCDs on the market.²³

The product's combination of performance and design values attracted attention, but the price triggered shock waves. The 700C listed at \$4,350. Toshiba reacted by replacing its \$5,499 T4400XC with the \$3,999 T44000, also a 486 notebook, but with a 9.5-inch display.²⁴ Prices on 80386-based notebooks tumbled. TFT LCDs had found an application that was expected to grow at 70 percent per year, and at the time, 10.4-inch displays appeared likely to establish themselves as a dominant design. Due to ongoing yield problems at DTI, IBM would need to buy quite a few of them from its competitors.

This proved difficult. By the end of 1992, IBM's ThinkPad success had triggered display shortages that rippled across all notebook suppliers. IBM struggled against a two-month backlog.²⁵ In early 1993, Microsoft introduced Windows 3.1, which displayed 256 colors. This added fuel to the color display fire, particularly for IBM-compatible computers, which used the Microsoft operating system. IBM PCC tried to translate its notebook market smash hit into FPD buying power, offering to source 10.4-inch displays from Sharp. Sharp's facilities were optimized to fabricate four 8.4-inch displays per 320 by 400 mm substrate. The engineers declared that the Gen 1 line had achieved yields of 60 percent, with monthly output of 90,000 displays. Sharp was offering these to high-volume customers for between \$800 and \$900.²⁶ If the company switched to 10.4-inch displays, throughput would fall to two units per substrate, resulting in wasted materials, reduced productivity, and increased costs.

Size Wars

In the wake of the ThinkPad introduction, Sharp, DTI, and NEC revived investment plans that had languished as yield improvements started to expand output more rapidly than demand could absorb. NEC hoped to quadruple production from 24,000 to 96,000 displays per month by the end of 1993 with a Generation 2 line. In July 1993, DTI's parents announced that they would invest 30 billion *yen*, or \$280 million, to triple capacity with a Gen 2 line at Himeji. DTI slated the new line to start up in the summer of 1994. DTI expected the TFT LCD market to continue the 70 percent yearly growth that began in 1992 through 1995.²⁷ Consistent with this forecast, Sharp also planned two Gen 2 lines to start up in mid-1994 to manufacture 10.4-inch TFTs.

After the ThinkPad popularized the high-end notebook computer, screen size stepped to the forefront of product features as a source of brand differentiation. This surprised many marketers. In the early 1990s, Sharp engineers had focused on minimizing power consumption to extend battery life. Sharp stuck with 8.4-inch displays, in part, because the smaller size consumed dramatically less power than a 10.4-inch display. Weight had also been an issue for most companies. NEC and Hitachi officials believed that customers ranked price above size.

IBM was perhaps the first notebook supplier to explore product attribute preferences with focus groups of users. Subsystem Technologies and Applications Lab director Steven Depp articulated the findings at a University of Michigan College of Engineering industry forum in November 1994. "You ask people what they like in our ThinkPad notebook, and one thing they like is the screen.... [W]hat you carry around for your mobile computer is basically the display." Users focused on brightness, image quality, and size. In the wake of these studies, IBM and Toshiba decided to invest in Gen 3 equipment for a DTI fab that would manufacture 12.1-inch displays. This size appeared especially promising because it offered a viewable area equivalent to that of a 14-inch CRT. As 10.4-inch prices continued to slide during the second half of 1995, Sharp and DTI people worked to bring up Generation 3 lines. The Sharp teams faced the added challenge of bringing up an intermediate generation (referred to as 2.5) based on stretching Generation 2 equipment to its absolute limits in substrate-size handling. Generation 3 lines carried automation, already an added feature of Generation 2, to a level of pervasive robotization. The substrates were too large for an operator to handle. Full cassettes used to transport substrates between manufacturing stages weighed about 80 pounds.

Because fewer humans were needed to operate Generation 3 lines, Sharp and DTI management expected the new fabs to achieve high yields rapidly. This

proved true for DTI, but not for Sharp. At DTI, experienced engineers from the Gen 1 and Gen 2 lines transferred from Himeji to the new Yasu location to bring the new line up. The reduced requirements for human intervention allowed DTI to redeploy its knowledge in this way without diminishing yields on the existing lines. In fact, DTI had maintained a stable headcount since 1994.²⁸ At Sharp the effort to bring up two lines at once, along with a new array process to increase the displays' aperture ratio, appeared to have too thinly spread its experienced engineers and operators. By May 1996, Sharp had conceded publicly that the Gen 3 line had proven itself a "major technical challenge," and that progress was slow. DTI's Gen 3 line was by then operating at full yields.²⁹ Having started up sometime in the fourth quarter of 1995

In April 1996, Sharp, Fujitsu, and Samsung announced that they would phase out 10.4-inch TFT LCDs as a result of plunging prices, after the size hit a low of \$300 per unit in March. Yet 12.1-inch displays were in short supply.³⁰ Many Gen 2 lines were switched to manufacturing two-up 12.1-inch displays. Merchants were getting spot prices of \$950 to \$1,450 for 12.1-inch displays, and offering volume prices of \$850 per unit to long-term customers. They could generate more revenues by producing two larger displays per substrate than four smaller ones.

Efforts to Establish Production in the United States

While the first high-volume, large-format TFT fabs were under construction in Japan, industry attention in the United States turned to the political arena rather than the factory floor. On July 17, 1990, the Advanced Display Manufacturers of America (ADMA) filed an antidumping petition³¹ with the U.S. Department of Commerce and the U.S. International Trade Commission (ITC). Established earlier in the year, ADMA's founding members included Optical Imaging Systems (OIS), Planar, Plasmaco, Photonics Technologies, Magnascreen, Cherry Corporation, and Electrolasma. All of the founding companies had received R&D contracts from the U.S. Defense Department's Defense Advanced Research Project Agency (DARPA). None had reached a decision to establish high-volume, large-format FPD production facilities.

The petition charged thirteen Japanese companies, including Sharp, Toshiba, Hosiden, and Hitachi, with predatory pricing of FPDs. The ITC authorized an investigation of the Japanese companies' production costs. Taking into account low production yields, the investigators concluded, fair market value for some of the companies' products exceeded the FPD prices on offer in the U.S. market (Hart 1993). Steep antidumping duties were authorized for several Japanese companies' TFT LCDs on August 15, 1991, at just about the same

time Sharp and DTI were bringing up their first Generation 1 lines. But in November 1992, OIS, which had been recently purchased by Guardian Industries and was the only U.S. domestic TFT LCD producer, requested that the duties be removed. On June 21, 1993, the U.S. Department of Commerce complied.

Despite its apparently innocuous conclusion, the antidumping petition permanently affected the course of FPD industry development within the U.S. Notebook producers, faced with the prospect of paying tariff-laden prices for the most advanced displays, immediately moved their assembly operations offshore. U.S. customs officials had ruled that the duties could not be levied on screens already incorporated into assembled goods. The duties also placed an artificial price floor under TFT LCDs at a time when the plants in Japan were struggling to move enough panels to drive production learning processes. Companies ramping up new fabs in Japan found they could charge close to the tariff-burdened price for displays selling there and to notebook assemblers producing in third markets. "This was an unexpected windfall," a respected former FPD market analyst later suggested. "The TFT manufacturers were able to put together quite a war chest, which allowed them to expand capacity more rapidly than expected."³²

The petition also validated a bias in many U.S. companies toward framing the industry knowledge race in terms of international rivalry among countries rather than global competition among firms. Many continued to look to government for the resources to compete. The widespread impression among U.S. industry participants held that the government needed to step up its involvement in the industry to counter Japanese government investments. In fact, Japanese government investments were minimal,³³ having directed companies' resources to a technological dead end that was subsequently abandoned.³⁴ The U.S. Public Television documentary series *Frontline* offered a one-sided assessment of the antidumping case and its aftermath, asserting that Japanese government support had played an important role in establishing the industry in Japan.³⁵ One defense industry journal reported with expansive inaccuracy in May 1993 that "the Japanese cornered LCD manufacturing capability by government investment of almost \$4 billion.' None of these reports reflected first-hand experience of industry circumstances in Japan. But in retrospect, they evoke the atmosphere of national urgency in which AT&T, Xerox, Standish, OIS, and the members of the ADMA entered negotiations with DARPA in 1993 to jointly fund an R&D consortium to help jump-start the industry in the United States."³⁷

The discussions concluded with the establishment of the U.S. Display Consortium (USDC) on July 20, 1993, as a nonprofit, public/private consortium with a primary mission of supporting the development of an FPD manufac-

turing infrastructure in the United States.³⁸ During its first six years of existence, the organization consisted of FPD producers, users, and equipment and materials suppliers with at least 50 percent U.S. ownership. The group based its structure on that of SEMATECH, another public/private consortium formed by DARPA and U.S. semiconductor producers and equipment makers in August 1987. According to one of several press releases issued to announce the consortium, however, important differences existed between the two programs. Unlike SEMATECH, the USDC would not establish an R&D and pilot manufacturing facility in which to test new equipment and materials.³⁹ This approach had not worked well for SEMATECH, because semiconductor manufacturers that were engaged in their own equipment development programs were reluctant to share a common factory floor (Young 1994). USDC development programs called for member manufacturers to test new equipment and materials in their own commercial fabs.

The absence from the membership rolls of high-volume manufacturers who could fulfill this role,⁴⁰ however, undermined the USDC's mission to "build the U.S. infrastructure required to support a world-class, U.S.-based manufacturing capability." As the centerpiece of its programs, the consortium identified U.S. industry development needs and invited proposals from members for projects to meet these objectives. Development teams consisted of equipment and materials suppliers working with an FPD producer that would serve as project coordinator and beta site. The USDC provided grants to defray project costs out of its DARPA funding, which the winning bidders matched at equal or greater value." But the USDC membership framework did not provide members with development partners who could qualify and integrate their equipment and materials innovations in the global, high-volume manufacturing context. No high-volume TFT LCD manufacturers existed on U.S. soil. Even if one had existed under foreign ownership, USDC practice would have pro-scribed contracting with it.⁴²

The issues that interposed between many U.S. equipment and materials manufacturers and high-volume producer/development partners reflected managerial mindsets as well as consortium policy and practice. Industry officials with influence over the consortium's project selection process did not believe that interdependence among equipment, materials, operators, and R&D scientists differed in any meaningful way between low- and high-volume production lines. Some did not regard the matter of line integration as important at all in designing new equipment, asserting that new pieces of equipment could, in principle, be qualified for high-volume production with data generated by "running them by themselves for a few days in a room."⁴³

But the question was not one of principle, but rather one of practice. In

practice, Generation 1 high-volume production lines were already running at high yields by the time the USDC's programs were established, and their operations had for some time been contributing vital knowledge to the design of Generation 2. Competing with existing equipment and materials makers would require companies to demonstrate a capability to integrate into existing production line systems, while making a clear contribution to both product features and yield enhancement. Participants in USDC development programs might have greatly benefited from opportunities to integrate new tools and materials into lines that incorporated process solutions reflecting the international state of the art. This would have required beta-siting in a production context with equipment and materials of diverse international origins.

U.S.-based producers, however, gave priority to U.S.-origin equipment when they established their fabs. At OIS, executives apologized for the few Japanese-origin tools on the production line.⁴⁴ Executives at Hyundai's ImageQuest affiliate in Fremont, California, expressed pride in creating a production line and process using equipment originating almost entirely in the United States. "We're more American than the USDC," president Scott Holmberg commented during a fab tour, noting as well that USDC ownership rules at the time precluded ImageQuest from membership.⁴⁵ USDC members wishing to qualify their project outcomes in a state-of-the-art production context needed their own international contacts and resources to do so. Photon Dynamics, whose project ranks as the USDC's most significant global success, was already working closely with Japanese and Korean customers as well as investors, when it accepted the USDC's first contract for a TFT LCD visual inspection system.⁴⁶ Few other members enjoyed similar advantages.

The FPD Industry Jumps to Korea

As demand for FPDs took off in the early 1990s, managers in the large, diversified Korean companies known as *chaebol* identified the FPD industry as an opportunity to leverage their existing semiconductor manufacturing capabilities. They also perceived a need to insulate their notebook computer businesses from TFT LCD supply shortages. Although Korean government guidance suggested an alliance to establish TFT production in Korea, management at Samsung, LG, and Hyundai chose to enter the industry independently and compete with each other. Distinctive approaches to international collaboration provided sources of competitive advantage for all three entrants, and helped two of them—Samsung and LG—win the two leading global market share positions by 2000. These independent international relationships took three forms: technical cooperation, strategic alliances, and long term contracts. Some relationships contained elements of all three.

Technical cooperation included equipment and materials supplier relationships, customer relationships, and R&D partnerships, including licensing. Technical cooperation relationships helped companies establish a knowledge base in current generation production technology, move rapidly into production, and create a foundation for continuous learning in ramping up successive new generation facilities. The Korean companies' positions as close followers to companies that had established high-volume production in Japan offered both advantages and challenges. Unlike U.S. companies that started up in the same time frame, they purchased equipment, process recipes, and extensive consulting services from the successful producers, equipment manufacturers, and materials makers. As a consequence, at Samsung and LG, Generation 2 installations came on-line and reached commercial yields relatively quickly—but not quickly enough to take advantage of the profits available to first movers.

Samsung and LG gained critical knowledge advantages by ramping up their Gen 2 lines, however, even in the face of price declines. Already committed to Generation 3 investments in the range of \$600 to \$800 million, both companies needed to leverage the knowledge gains from Generation 2, particularly experienced operators, to move rapidly forward. Samsung entered Generation 3 in late 1996, reaching commercial yields in early 1997, hot on the heels of DTI and Sharp. LG followed with its Generation 3 line in the second half of the year, but running a slightly larger substrate that offered cost economies while optimized for slightly larger displays.

Technical cooperation relationships as well as *equity-based strategic alliances* also helped the companies to cut costs in the face of continuous price declines, and to differentiate their products. Samsung's alliance with Corning, Samsung-Corning Precision Glass Co., placed it alongside the leading substrate supplier in the forefront of glass innovation. Samsung-Corning opened its first fusion glass plant in Korea in 1995.⁴⁷ The relationship contributed to increased efficiency and helped Samsung approach generational transitions with confidence and foresight. In 1995, Samsung entered into a cross-licensing agreement with the Japanese firm Fujitsu, a fellow late TFT LCD entrant. Fujitsu provided its wide viewing-angle technology in exchange for Samsung's high-aperture ratio, brightness-enhancing technology.⁴⁸

LG management regarded technical cooperation as an even more central element in strategy, in part as a means of compensating for the company's size difference with Samsung and Hyundai. "Our philosophy is not to try to do everything for ourselves," said Choon-Rae Lee, managing director of LG's LCD Division. "We will work with anyone who can add a cost or differentiation advantage."⁴⁹ Management also set a goal to excel in particle control and yield enhancement. At least two technical cooperation agreements significantly contributed. In 1994, LG entered a \$30 million joint venture with Alps Electric, a

Japanese components firm, to develop ultraclean manufacturing technology at Alps Central Laboratory in Japan. LG implemented the technology for the first time on its Generation 3 line at Kumi.⁵⁰ Its work with Photon Dynamics on TFT array test equipment proved crucial to meeting LG's zero-defect objective,⁵¹ and helped the company gain a five-year, \$1 billion contract to supply 12.1-inch displays to Compaq, despite having only one year of volume production experience.⁵²

The Korean entrants set strategic objectives to profitably seize both differentiation and cost leadership advantages by establishing primacy or at least close followership in the transitions to Gen 3, and subsequently Gen 3-plus high-volume production technology. They also pushed process technology forward through other productivity enhancements, including increased array testing, inspection, and clean room particle control.⁵³ Running state-of-the-art Gen 1 and Gen 2 lines at pilot quantities, the companies began to accumulate experience to selectively enter equipment and materials manufacturing as well as high-volume Generation 3 production. Samsung, for example, achieved commercial yields on its first high-volume line, a Generation 2, in July 1995,⁵⁴ at approximately the same time as Sharp and DTI were starting up their Gen 3 lines. The company started up the industry's next Gen 3 line in October 1996,⁵⁵ and it broke ground for a Gen 3-plus line to handle 600 by 720 mm substrates in January 1997.⁵⁶ During the same period, the company developed independent materials and equipment capabilities in several components including glass substrates in its Samsung-Corning joint venture.

Long term contracts as well as equity-based alliances with customers played an important role in sustaining continuity. Only Hyundai delayed ramping up its Generation 2 line, which it had installed by the end of 1995, hoping for stabilization in 10.4-inch prices.⁵⁷ Technical cooperation tied to a long-term sales agreement with Toshiba helped the company to overcome subsequent delays in achieving commercial yields,⁵⁸ and to reduce further delays in moving to Generation 3. Hyundai's transition to Generation 3-plus, like that of all of the Korean producers, was complicated by external events of global significance.

Financial crisis gripped Asia in the late 1990s, placing the Korean TFT LCD producers' ambitious expansion plans at the mercy of an investment capital crunch. Long-term contracts assumed increasingly vital roles in helping to continue next generation investments, while at the same time ensuring notebook computer companies of an increasing supply of the most advanced display components to sustain their growing businesses. In November 1999, Hyundai concluded contracts with four notebook manufacturers—including IBM, Compaq, and Gateway—for five years' sales of \$8 billion.⁵⁹ In March 2000, Hyundai announced that it hoped to start up a next generation fab at Ichon, raising the company's planned production capacity to 1.5 million TFT LCDs annually.⁶⁰

In July 1999, Apple Computer revealed plans to invest \$100 million in Samsung in order to speed the construction of new production capacity for TFT LCDs.⁶¹ In October 1999, Samsung signed a five-year contract worth \$8.5 billion to supply TFT LCD displays to Dell Computer Corporation.⁶² Having doubled capacity in 1999, Samsung was on track to open the world's first fab to utilize 730 by 930 mm substrates.⁶³ Industry sources differed on what number to designate the new generation. One called it "Generation 3.7" (see Law 2000), others 3.5-plus. Samsung preferred "Generation 4." Many industry participants still waited for a fabled one-meter-square substrate to bear that designation.

Management decisions to expand production and continue TFT LCD generational progressions in the face of the Asian financial crisis surprised industry observers. But these decisions thrust Samsung and LG well ahead of more cautious producers in Japan as well as the United States, and created two very profitable businesses.

LG's TFT LCD business was so profitable, in fact, that management struck a defiant pose when government's crisis plans for restructuring Korean industry demanded the combination of LG Semiconductor with Hyundai's semiconductor business. Unhappy about any such plan, management made it clear that the LCD Division's assets, with a book value of about \$1 billion, were not on the table.⁶⁴

International markets ratified management's decision with the May 1999 announcement that Royal Philips Electronics of the Netherlands would acquire 50 percent of LG's LCD unit in exchange for an investment of \$1.6 billion in the joint venture. LG.Philips LCD was established in July 1999, and officially began operations in September 1999.⁶⁵

In 1999, Samsung's global FPD market share, ranked first, stood at 18.8 percent. LG.Philips's share, ranked second, stood at 16.2 percent. Korean companies, staffed by many U.S.-educated engineers and managers, had broken Japan-based sources' short-lived near monopoly over high-volume, large-format color TFT LCD production. Furthermore, the Korean companies did it with the cooperation of equipment makers, materials producers, and TFT LCD producers centered in Japan. Philips established a European presence in high volume even more rapidly, seizing opportunities for TFT LCD production partnership that every U.S. company except IBM had neglected for years.

Conclusion: Cluster Busting

Many managers and public policy makers believe that when a scale-intensive high-tech industry concentrates in one country, companies from other countries get easily locked out. Debates about how countries should respond to high-tech industry concentration in other countries have centered on either

building countervailing industry concentrations (known as clusters) at home or establishing facilities within the foreign cluster itself. Public policy-makers and business strategists have turned for guidance to economic geography, which offers a research tradition that explains why certain industries develop great centers of creativity and productivity in particular world regions but not others (e.g., Porter 1990, 1998). Attention has focused on the importance of country- or region-specific management or innovation systems (see Kogut, this volume), path-dependent historical developments, institutions such as great universities and national research laboratories, and the importance of knowledge spillovers that occur among companies through common suppliers, consultants, customers, job changers, and the social and professional networks that emerge as part of the local industry community.

The FPD experience demonstrated how easily these ideas can be misappropriated as guides to corporate strategy and public policy, particularly in the early days of a new high-technology industry. Much U.S. thinking about the FPD industry has foundered on the notion that the vitality of the FPD industry in Japan somehow arose when factors intrinsic to Japan combined (illegitimately!) with a U.S. invention. The proposed factors ranged widely across well-known Japanese business institutions and country capabilities, including the availability of patient capital, the coordinative power of government, and the meticulous rigor of Japanese engineers and production workers. None of these factors can explain the collision of individual creativity with the global innovation system that catalyzed the beginnings of LCD research in Japan.

Cluster thinking confused many observers of the FPD industry's emergence, because it draws attention to stable internal institutions and knowledge that may offer countries some degree of autonomy in world markets. The Northern Italian high-fashion textile industry, for example, may well have enjoyed an ability to dictate important trends in high-end fabric design for a time. But such autonomy is increasingly short-lived. Even traditional industries like high-quality fabric have diffused to Asia in recent years because of globalization. Focusing on clusters can create a false sense of permanence for business strategy.

More important, high-technology industries increasingly emerge from a convergence of local with global factors and knowledge that catalyzes rapid accumulation of new knowledge. In terms of Kenney's five dynamics (Chapter 1), FPDs represented a principal but volatile focus of value creation in the segmented supply chain for notebook computers. The high-volume FPD industry originated in a convergence of knowledge drawn from a variety of countries. The knowledge moved in global markets through the transport of people, equipment, and materials, and the communication of ideas both within and across national borders. The industry's concentration in Japan in its early phases was a consequence—not a cause—of the rapid acceleration of knowl-

edge accumulation around FPD technology in the 1980s. As the mass consumer market for notebook computers emerged in the 1990s, industry learning continued to be catalyzed by global forces, including the Internet, growing demand sparked by firms' continual efforts to reduce costs, and continually changing consumer markets for technology products that incorporated FPDs.

State-of-the-art business strategy prescriptions for entering the FPD industry in the early 1990s would have suggested establishing operations in Japan. But potential market entrants that waited until the FPD industry's strength in Japan had become widely evident were already too late to play leadership roles in that phase of the industry's development. Leadership was important, because only leaders made any money. As a consequence of the financial stress that many companies in Japan experienced, it later became possible to buy in using an acquisition strategy. Only one company, Philips, was wise enough to do so, by entering an alliance with Hosiden, a small, merchant producer, which it ultimately acquired. The foundations for Philips's visionary move were established years earlier in its close post-World War II relationship with Matsushita, which had played an important advisory role in the establishment of Hosiden. Philips had also gained timely industry awareness in an expensive, but ultimately unsuccessful, effort to establish FPD manufacturing in Europe. In general, if a company discovers the attractiveness of an industry because a cluster has emerged somewhere, its management has already experienced a fatal failure of foresight.

U.S. public policy prescriptions for the FPD industry focused on finding government-led strategies to remedy the U.S. market's presumed failure to offer incentives for local firms to establish facilities on U.S. soil. In economic theory, market failure offers one of few justifications for government economic intervention in markets. International markets can fail for many reasons. Knowledge markets are especially prone to failure because one firm's ownership of knowledge does not preclude other firms from having it, whether or not they pay for it. Firms face difficulties in negotiating knowledge exchanges: price-setting by nature involves some degree of disclosure, and disclosure of information reduces incentives to pay (Arrow 1971). Particularly in the United States, these difficulties have predisposed managers to focus on strategies that restrict outsiders' access to their firms' knowledge, rather than on ways of profitably sharing what they know with competitors, collaborators, suppliers, and customers. These concerns intensify for most companies when they manage international businesses.

The heated pace of high-technology competition inverted this conventional logic for some U.S. firms. As a consequence, they became key players in the FPD industry. But the U.S. government fell behind by implementing policies to encourage domestic FPD industry cooperation in preference to international

market activity. These efforts to create a countervailing FPD presence in the United States created incentives for U.S. companies to cut themselves off from the suppliers, customers, complementary assets, and knowledge streams that were creating the industry. U.S. taxpayers and some entrepreneurs in the FPD industry paid a heavy price for these failed policies in the 1990s. Instead of establishing high-volume FPD manufacturing in the United States, another generation of progress was lost.

Intensive research on the evolution of the global FPD industry has persuaded us that high-tech industry concentration in one country or world region does not lock companies from elsewhere out unless they close the door on themselves. New high-technology industries often bubble under the surface for many years in several countries before they suddenly achieve critical mass and commercialize at global scale in one or more of them. Once a new industry emerges, continuity in knowledge accumulation, the pace of technical advance, and the commercial and social relationships that drive knowledge creation in the industry reinforce one another.

It is impossible to predict the exact timing and location in the world where any given technology will commercialize and a global industry emerge. But it is possible for companies to design management processes that positively affect their probabilities of participating. Companies with affiliates in a country or region where an industry emerges have as good a shot as local companies at taking integral positions, provided their managers can fully leverage local organizational capabilities with global technological capabilities as these opportunities arise. In the successful companies in our study, local managers functioned in peer networks as global managers. Local initiatives served as primary means to identify and go after global opportunities. Long-standing corporate research traditions in underlying technologies combined with strong local operations to establish these companies' stakes in the rapid accumulation of knowledge assets associated with the FPD industry's emergence. Developing such a knowledge stake formed a necessary condition for successful physical asset deployments anywhere in the world, including at home.

Notes

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1. "RCA Develops a New Visual Display Means Using Liquid Crystal," *Wall Street Journal*, May 29, 1968, 4.

2. Johnstone's (1999) account conveys an optimism that may have been privately expressed by the researchers, particularly Heilmeier, whom he interviewed in March 1994. Most of the contemporary published journalistic accounts we accessed conveyed cautious or neutral assessments of the technology's likely time-to-market in television form. See, for example, "Liquid Crystals," *Science Digest*, December 1968, 32-34. Yet journalists who were working in the field of consumer electronics around the time of the announcement and in the years following remember a sense of immediacy and excitement that contemporary journalistic style may have tempered in print. Telephone discussion, Robert Angus, former senior editor of *Consumer Electronics Monthly*, August 5, 2000.

3. According to Johnstone (1999: 38), an earlier fully electronic calculator by Sony, the SOBAX, never advanced beyond the prototype stage.

4. "Sharp Develops Thin, 14-Inch TV Monitor Light Enough to Hang on Wall," *Asahi News Service*, June 17, 1988; "Toshiba, IBM Claim Largest Color Liquid Crystal Display," *Japan Economic Newswire*, September 21, 1988, accessed via Lexis-Nexis, September 18, 2000.

5. Interview, Norihiko Naono, director of business development, Rambus K.K., (former Nomura analyst), Tokyo, Japan, October 17, 1996.

6. "Toshiba, IBM Set Plant for Large LCDs," *Los Angeles Times*, August 30, 1989, Business Section, Part A, 3.

7. Interview, Kanro Sato, general manager, Liquid Crystal Display Division, Toshiba Corporation, Tokyo, Japan, June 12, 1997.

8. Interview. Kawanishi was executive vice president and head of Toshiba's world-wide electronics components and semiconductor businesses and later held the title of senior executive vice president for partnerships and alliances. When the authors met with him on November 15, 1996, at Toshiba's Tokyo headquarters, he held the title of "senior advisor," and played a visible emeritus role within the company.

9. "Toshiba, IBM Japan Link to Make LCDs," *Nihon Keizai Shimbun (Japan Economic Journal)*, September 9, 1989, 13.

10. "Sharp Up for Volume Color LCD Production," *Jiji Press Ticker Service*, October 12, 1989, accessed via Lexis-Nexis, September 18, 2000.

11. Yuko Inoue, "Market Slump Snags Color LCD Venture; Toshiba, IBM Revise Targets but Remain Optimistic," *Nikkei Weekly*, April 25, 1992, 8.

12. "Toshiba-IBM LCD Venture Firm Goes On-Line," *Japan Economic Newswire*, Kyodo News Service, May 15, 1991, accessed via Lexis-Nexis, September 26, 2000.

13. Interview, Robert Wisnieff, manager, flat panel display fabrication, International Business Machines Corporation (IBM), Thomas J. Watson Research Center, Yorktown Heights, New York, July 22, 1996.

14. Steven Butler, "The Art of Perfection: Steven Butler Explains How a Single Speck of Dust Creates Havoc with the Way Liquid Crystal Displays Are Made," *The Financial Times*, London, April 16, 1992, Technology Section, 14.

15. Bill Snyder, "Full Speed Ahead: Toshiba Corp. Plans Ambitious Expansion," *PC Week*, November 7, 1994, A1.

16. CVD tools coat extremely thin films of metals and chemicals on glass as part of the procedure that forms the millions of transistors built into a TFT LCD.

17. Yuko Inoue, "Production Woes Stall Mass-Market Hope for Color LCDs," *Nikkei*

Weekly, September 21, 1991, 8. The article reported that Nomura analysts had identified color filters and CVD efficiency as "two major headaches for LCD parts makers, partly due to limited competition." Color filters were expensive and in short supply, and CVD inefficient, causing production bottlenecks.

18. Brooke Crothers and Jack Robertson, "IBM/Toshiba LCD Unit Sees Yields Rise to 50 Percent," *Electronic News*, July 6, 1992, accessed via Lexis-Nexis, July 1999.

19. Yuko Inoue, see note 17.

20. This represents a conservative interpretation. The outcomes of such analyses depend critically on how many generations the analyst judges to have passed. This is in part an issue of industry politics, as companies may claim territory by referring to their own incremental changes as generation changes, or by discounting the generational claims of others.

21. Interview, Toru Shima, president, Display Technologies, Inc. (DTI), Himeji, Japan, June 2, 1997.

22. Steven Butler, see note 14.

23. "Color Display, Built-in Pointing Device Lead IBM ThinkPad Line," PR Newswire, October 5, 1992, accessed via Nexis-Lexis, August 15, 2000. One month after the product announcement, the editors of *PC/Computing* presented IBM with the "Most Valuable Product" (MVP) award at the annual "Best Hardware and Software of the Year" award ceremonies in Las Vegas before the opening of COMDEX/Fall '92. IBM ThinkPad 700C Named Best Color Notebook Computer, PR Newswire, November 16, 1992, accessed via Lexis-Nexis, August 1999.

24. Kristina Sullivan, "Color Notebooks Also Hit by PC Price Wars," *PC Week*, November 16, 1992, accessed via Lexis-Nexis, August 15, 2000.

25. Adam Greenberg, Brooke Crothers, and Jonathan Cassell, "Notebook Shortage Blamed on LCDs," *Electronic News*, December 14, 1992, 1.

26. Brooke Crothers, "Sharp Sticks to Displays with High Yield Record," *Electronic News*, April 12, 1993, 15. The source quoted regarding the IBM PCC overture to Sharp was Norihiko Naono (see note 5), at the time a Nomura Research Institute analyst.

27. "Toshiba-IBM Japan Venture to Boost TFT LCD Output," Japan Economic Newswire, Kyodo News Service, July 8, 1993, accessed via Lexis-Nexis, September 26, 2000.

28. Toru Shima (see note 21) gave DTI employment as 1,451 in June 1997.

29. Jack Robertson, "FPD Players Split over Glass Mfg. Strategy—Can't Decide on Shift to Larger Screens," *Electronic Buyers' News*, May 20, 1996, accessed via Lexis-Nexis, September 26, 2000.

30. Jack Robertson, "Suppliers Phase Out 10.4" Displays," *Electronic Buyers' News*, April 22, 1996, 1.

31. Dumping is defined as selling abroad at prices below fair market value in the home market.

32. Interview, Norihiko Naono (see note 5).

33. Norihiko Naono, "Japan FPD Market: Industry at Large," *Electronic News*, September 7, 1992, 10. This point was reiterated repeatedly in our research by most U.S. and all Japanese government officials, although some U.S. officials had the opposite impression.

34. In 1989, MITI encouraged FPD producers to form the Giant Technology Corporation with a funding level of about \$28 million to pursue nonlithographic printing

techniques to fabricate very-large-format TFTs. The formula of cost sharing between business and government is subject to dispute (see also Borrus and Hart 1994). This program proved itself a major misdirection of corporate resources, according to Steven W Depp, director, Subsystem Technologies and Applications Laboratory, International Business Machines Corporation (IBM), Thomas J. Watson Research Center, Yorktown Heights, NY. Telephone discussion with Lenway and Murtha, November 14, 2000.

35. Martin Koughan, writer/producer/reporter, and David Ewing, director, "Losing the War with Japan," first broadcast on U.S. Public Television's *Frontline*, November 19, 1991.

36. Sheila Galatowitsch, "LCDs Run Away with Military Flat Panel Market," *Defense Electronics*, May 1993, 25.

37. "Pentagon Picks Partner for Flat Screens," *San Francisco Chronicle*, February 5, 1992, F3. The discussions reflected the companies' response, submitted January 18, 1993, to a request for proposals issued by DARPA nine months earlier.

38. "SEMI Forms FPD Division to Serve U.S. Display Consortium," *Business Wire*, July 20, 1993, accessed via Lexis-Nexis, summer 1994.

39. Ibid.

40. IBM was a member of the consortium's user group, but not the producer group.

41. By 1998, projects budgeted at more than \$95 million had been funded in this way.

42. For a discussion of the critical role of practice in learning and knowledge creation, see Brown and Duguid (2000a), esp. chs. 4 and 5.

43. Interview, industry official with Murtha and Lenway, Silicon Valley, summer 1996.

44. Interview, Rex Tapp, president and CEO, Optical Imaging Systems, Inc. (OIS), Northville, Michigan, May 7, 1996.

45. Interview, Scott Holmberg, president and CEO, ImageQuest Technologies, Inc., Fremont, California, June 25, 1996.

46. Photon Dynamics raised capital in Japan with the help of the Nomura and Daiwa Securities firms beginning in 1991. Bob Johnstone, "Research and Innovation: Spot the Mistake," *Far Eastern Economic Review*, July 16, 1992, 66. The Korean company LG also took a position in the company, according to Choon-Rae Lee, managing director, LCD Division, LG Electronics, Inc., Seoul, Korea, December 6, 1996.

47. Samsung and Corning established their first joint venture in 1973 to manufacture CRT glass. See www.samsungcorning.co.kr, accessed November 16, 1996.

48. Samsung website: www.sec.samsung.co.kr, accessed November 16, 1996.

49. Interview, Choon-Rae Lee (see note 46).

50. "South Korea, Taiwan Firms Raid Japanese Staffs, Buy Technology," *Nikkei Weekly*, March 3, 1997, 20.

51. De facto industry standards permit shipping goods with as many as five defective pixels.

52. "LG to Supply \$1 Billion Worth of TFT LCDs to Compaq," *Korea Economic Weekly*, December 12, 1996, accessed via Lexis-Nexis, June 1997.

53. "Korean TFT LCD Producers Expected to Match DRAM Share by End of the Decade," *PR Newswire*, August 27, 1997, accessed via Lexis-Nexis, July/August 2000.

54. Interview, Jun H. Souk, executive director, AMLCD R&D, Semiconductor Business, Samsung Electronics Co., Kiheung, Korea, December 5, 1996.

55. Ibid.

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