May 2004

Competition through Institutional Form: the Case of Cluster Tool Standards

Richard N. Langlois
University of Connecticut

University of Connecticut

Department of Economics Working Paper Series

Competition through Institutional Form: the Case of Cluster Tool Standards

Richard N. Langlois
University of Connecticut

Working Paper 2004-10

May 2004

341 Mansfield Road, Unit 1063
Storrs, CT 06269–1063
Phone: (860) 486–3022
Fax: (860) 486–4463
http://www.econ.uconn.edu/

Abstract

Industrial economists tend to think of competition as occurring between atomic units called ”firms.” Theorists of organization tend to think about the choice among various kinds of organizational structures – what Langlois and Robertson (1995) call ”business institutions.” But few have thought about the choice of business institution as a competitive weapon. This essay will examine, and attempt to learn from, a case in which choice of organizational form is in fact a major element of competition. Cluster tools, a type of equipment for manufacturing semiconductors, are becoming increasingly important as manufacturers attempt to pack more and more circuits on a chip. Within the U. S. industry, competition for these devices is divided between a large vertically integrated firm, Applied Materials, that designs and builds largely internally according to its own specifications and a large fringe of smaller, more specialized competitors. These latter have responded to the competition from Applied by creating a common set of technical interface standards, called the Modular Equipment Standards Committee (MESC) standards. Rather than a battle of the standards, the current situation might best be thought of as a battle of alternative development paths: the closed system of Applied Materials, with its significant internal economies of scale and scope, and the open modular system of the competitive fringe, driven by external economies of standardization. At this point, the forces favoring the integrated development path are more-or-less evenly balanced against the forces favoring the path of technical standardization. I analyze these forces in terms of the tradeoff between the benefits of systemic innovation and systemic coordination on the one hand and the benefits of external economies of scope and modular innovation on the other. Although standards have so far kept the competitive fringe in the ballgame, modularity in the industry may ultimately take a different, and somewhat more familiar, form, as some of the larger firms adhering to the standards become broadly capable systems integrators who outsource manufacturing to specialized suppliers of subsystems.

Paper for a conference on Standards and Public Policy, Federal Reserve Bank of Chicago, May 13-14, 2004

Introduction.

Industrial economists tend to think of competition as occurring between atomic units called "firms." Theorists of organization tend to think about the choice among various kinds of organizational structures – what Langlois and Robertson (1995) call "business institutions." But few have thought about the choice of business institution as a competitive weapon.[1]

In this essay I examine, and attempt to learn from, a case in which choice of organizational form is in fact a major element of competition. Cluster tools, a type of equipment for manufacturing semiconductors, are becoming increasingly important as manufacturers attempt to pack more and more circuits on a chip. Within the U. S. industry, competition for these devices is divided between a large vertically integrated firm, Applied Materials, that designs and builds largely internally according to its own specifications and a large fringe of smaller, more specialized competitors. These latter have responded to the competition from Applied by creating a common set of technical interface standards, called the Modular Equipment Standards Committee (MESC) standards.

Rather than a battle of the standards, the current situation might best be thought of as a battle of alternative development paths: the closed system of

1 One exception was Schumpeter, who listed "new forms of industrial organization" as among the sources of the "fundamental impulse that sets and keeps the capitalist engine in motion" (Schumpeter 1942 [1976], p. 82).

Applied Materials, with its significant internal economies of scale and scope, and the open modular system of the competitive fringe, driven by external economies of standardization. At this point, the forces favoring the integrated development path are more-or-less evenly balanced against the forces favoring the path of technical standardization. I analyze these forces in terms of the tradeoff between the benefits of systemic innovation and systemic coordination on the one hand and the benefits of external economies of scope and modular innovation on the other. Although standards have so far kept the competitive fringe in the ballgame, modularity in the industry may ultimately take a different, and somewhat more familiar, form, as some of the larger firms adhering to the standards become broadly capable systems integrators who outsource manufacturing to specialized suppliers of subsystems.

Background.

The integrated circuit was very much an American invention, developed independently but simultaneously by researchers at Texas Instruments and Fairchild in 1959. As an integrated-circuit industry grew out of the discrete-transistor industry, American firms dominated, both in the fabrication of the chips themselves and in the manufacture of the equipment to make chips. In the early days, semiconductor firms developed much of their own process equipment, often in collaboration with firms in the scientific-equipment industry.

Gradually, a distinct semiconductor-equipment industry emerged. In 1980, nine out of the top ten firms were American. (See Table 1.)

With the rise of Japanese IC fabrication in the 1980s and the loss of American market share in dynamic random-access memories (DRAMs), American dominance in semiconductor equipment also declined. By 1990, only four of the top ten were American, and only Applied Materials remained among the top five. (See Table 1.) Between 1980 and 1988, worldwide sales of equipment for lithography, chemical vapor deposition (CVD), and ion implantation quadrupled; during the same period, the American share fell from 75 to 49 per cent, while the Japanese share rose from 18 per cent to 39 per cent (Department of Commerce 1991). The Japanese success was most pronounced in lithography equipment, automatic test equipment, and assembly and packaging equipment.

1980		1990		2000	
Company	**Sales**	**Company**	**Sales**	**Company**	**Sales**
Perkin-Elmer (US)	151	Tokyo Electron Ltd (J)	706	Applied Materials (US)	10,410
GCA (US)	116	Nikon (J)	692	Tokyo Electron Ltd (J)	5,142
Applied Materials (US)	115	Applied Materials (US)	572	Nikon (J)	2,432
Fairchild TSG (US)	105	Advantest (J)	423	Teradyne (US)	2,044
Varian (US)	90	Canon (J)	421	ASM Lithography (E)	2,016
Teradyne (US)	83	Hitachi (J)	304	KLA-Tencor (US)	2,003
Eaton (US)	79	General Signal-GCA (US)	286	Advantest (J)	1,865
General Signal (US)	57	Varian (US)	285	Lam Research (US)	1,627
Kulicke and Soffa (US)	47	Teradyne (US)	215	Canon (J)	1,418
Takeda Riken (J)	46	Silicon Valley Group (US)	204	Dainippon Screen (J)	1,390

Note: nominal dollars in millions.
US = U. S. firm; J = Japanese; E = European.

Source: VLSI Research.

Table 1: Top 10 Semiconductor-equipment suppliers, 1980, 1990, and 2000.

The decline in American pre-eminence in semiconductor equipment generated much the same *angst* as the better-known decline in American market share in DRAMs. A number of groups, including the National Advisory Committee on Semiconductors, issued dire warnings (NACS 1990). And Sematech, the government-industry consortium, quickly began defining much of its role as helping to reverse the fortunes of the American equipment industry (Robertson 1991). The diagnosis of the equipment industry's problems was similar to that for the semiconductor industry as a whole: the American industry suffered from excess "fragmentation" and insufficient vertical integration. In one of the few contemporary academic examinations of this industry, a study by the Berkeley Roundtable on the International Economy concluded that

> with regard to both the generation of learning in production and the appropriation of economic returns from such learning, the U.S. semiconductor equipment and device industries are structurally disadvantaged relative to the Japanese. The Japanese have evolved an industrial model that combines higher levels of concentration of both chip and equipment suppliers with quasiintegration between them, whereas the American industry is characterized by levels of concentration that, by comparison, are too low *and* [by] excessive vertical disintegration (that is, an absence of mechanisms to coordinate their learning and investment processes) (Stowsky 1989, p. 243, emphasis original).

By 1992, however, the situation had changed markedly, and American firms regained and retained the lead in market share in semiconductors.[2] Behind this resurgence lay a number of factors. American firms had increased their attention to manufacturing quality in response to the Japanese challenge. More importantly, the decentralized and "fragmented" structure of the industry proved innovative and responsive in a world in which production was becoming international and in which an increasingly modular technology of design permitted efficient vertical specialization. Most importantly, American manufacturers benefited from a favorable shift in demand away from mass-produced DRAMs and toward design-intensive chips and microprocessors.

The rising tide of the American resurgence and of the internationalization of chip production also raised the boats of the American equipment industry.[3]

---

2 For a detailed history and analysis of the fall and rise of the American semiconductor industry, on which the remainder of this paragraph draws, see Langlois and Steinmueller (1999).

3 This paragraph draws on Macher, Mowery, and Hodges (1999, p. 266).

During the nadir of American fortunes in the period 1984-1991, Japanese semiconductor companies were responsible for nearly half of all the capital expenditures in the industry. By 1997, however, the Japanese share of those expenditures had fallen to 25 per cent despite an absolute increase. This reflected in part an increase in American investment in response to the booming personal computer market, to which American semiconductor makers (notably Intel) were closely tied. American equipment makers benefited, since, in both the U. S. and Japan, manufacturers rely heavily on their own indigenous equipment industries.[4] At the same time, manufacturers in parts of Asia other than Japan, principally Korea and Taiwan, had doubled their share of capital spending over that period, to a level that together exceeded Japan's in 1996. This provided a fertile new market for American equipment makers. So-called silicon foundries – firms in the Far East and elsewhere that specialize in the manufacturing stage only – typically produce American-designed products that involve multiple layers with metal interconnections and require sophisticated "mid-process" technology for tasks like CVD and PVD (physical vapor deposition – also called

---

[4] In 1997, both the U. S. and Japan sourced about 75 per cent of their equipment from their respective domestic industries, according to data from VLSI Research (cited in Macher, Mowery, and Hodges (1999), pp. 252 and 266). The link between manufacturers and equipment makers is arguably tighter in Japan, however, where manufacturers often own their own equipment firms (e. g., Hitachi) and where, at least in the view of American industry participants, the relationship of equipment makers to manufacturers is generally more dependent and even "deskilling" of the equipment makers (Langlois 2000). The relative independence of American equipment firms has been an asset in export markets outside Japan.

"sputtering"). These are areas in which American equipment firms have specialized and excelled.

Indeed, there has arisen something of an international division of labor in the industry, partly by default. We can think of the more than 500 process steps in semiconductor fabrication as grouped into three phases akin to the steps in

Rank	**Company**	**Sales**
1	Applied Materials (US)	4.8
2	Tokyo Electron (J)	3.3
3	ASM Lithography (E)	1.8
4	Nikon (J)	1.3
5	KLA-Tencor (US)	1.3
6	Canon (J)	1.2
7	Advantest (J)	1.1
8	Dainippon Screen (J)	1.0
9	Novellus (US)	0.9
10	Hitachi (J)	0.8
11	Lam Research (US)	0.7
12	Teradyne (US)	0.7
13	Agilent (US)	0.7
14	ASM International (E)	0.6
15	Yokogawa Electric (J)	0.5

Note: Dollars in millions.
US = U. S. firm; J = Japanese; E = European.

Source: VLSI Research.

Table 2: Top 15 Semiconductor-equipment suppliers, 2003

photo developing. The front-end steps involve optical lithography, the process that projects the circuit design onto the silicon wafers in the manner of a darkroom enlarger. The middle steps involve the processing of the wafers in analogy with the business of plunging a photo print into successive chemical baths. And the back-end steps involve testing the finished wafers and packaging them to into individual ICs. Just as American manufacturers of DRAMs virtually disappeared during the Japanese ascendancy of the 1980s, so too did American suppliers of lithography equipment – a field that, like DRAMs, Americans had pioneered. Optical giants Nikon and Canon accounted for much of the Japanese market share in that decade, and they are joined today by the Dutch firm ASM Lithography. As we saw, test equipment was also an area of Japanese dominance, but that is changing with the ascendancy of American firms like KLA-Tencor, Teradyne, and Agilent (a spin-off from Hewlett-Packard).[5] (See Table 2.)

It is in the mid-process stages, however, that American firms have retained and indeed increased their strength. Here a single firm, Applied Materials, accounts for much of that success. By 1992, Applied Materials had overtaken its Japanese rivals to become the largest semiconductor-equipment firm in the world. In the boom year 2000, Applied generated revenues of over

---

[5] At the same time, the market for "test" equipment has shifted toward metrology – real-time monitoring and testing of product and process rather than merely testing of the final product.

$10 billion, almost double those of the next largest firm, Tokyo Electron (TEL), an independent concern that is essentially Applied's Japanese counterpart and its principal international rival.[6] (See Table 1.) But Applied is not without American competitors. This single large firm is ringed by an array of smaller, more specialized, less vertically integrated firms led by Novellus and Lam Research. (See Table 2.) And herein lies our story. To tell that story properly, however, we need to know more about the mid-process technology of semiconductor fabrication.

Single-wafer processing and cluster tools.

The traditional approach to the mass production of semiconductors has been batch processing. Silicon wafers, each containing what will become many separate chips, move through the various steps in batches, queuing up when necessary in work-in-process (WIP) inventories. For example, a large vertical furnace may process more than 200 wafers at a time. Increasingly, however, batch processing is being replaced by single-wafer processing, that is, systems that process one wafer at a time. This is analogous to the continuous-throughput techniques that have largely supplanted batch-processing approaches in the chemical industries.[7] In today's fabs – as semiconductor manufacturing facilities

---

6 In fact, however, the product categories in which Applied and TEC compete directly account for only a small fraction of TEC's sales (InfoNet 2004a, p. 4-27).

7 This is an analogy one hears often in this industry. Indeed, it is more than just an analogy, as wafer fabrication involves a series of what are basically chemical-engineering processes.

are called – about 70 per cent of process steps use single-wafer techniques, with batch processing restricted to so-called hot-wall thermal steps (furnaces) and "wet-bench" steps that are literally like plunging a photo print in a chemical bath (InfoNet 2004c, p. 3-5).

Single-wafer techniques are likely to become increasingly significant as semiconductor line widths decrease below 0.25 microns.[8] Already many hot-wall processes have been replaced by more thermally efficient single-wafer technologies like rapid thermal processing (RTP), and wet-bench approaches are yielding to "dry" alternatives suitable for single-wafer processing. Indeed, a completely single-wafer fab is entirely feasible. By 1993, Texas Instruments's Microelectronics Manufacturing Science and Technology (MMST) project, funded partially by the U. S. Department of Defense, had demonstrated a small-scale fully single-wafer production line (Doering and Nishi 2001). More recently, Japanese start-up Trecenti Technologies has claimed to have put in production a fully single-wafer 300-mm manufacturing facility (Ikeda *et al*. 2003). Among the major players, the Taiwanese foundry companies Taiwan Semiconductor Manufacturing and United Microelectronics have apparently moved the farthest in the direction of single-wafer processing (Bass and Christensen 2002).

The advantages of single-wafer processing are several (Singh, *et al*. 2003). Like most industries, semiconductor fabrication has its share of waggish jargon. One of these is the "milk carton" principle. If you needed to keep a single carton of milk cold, you wouldn't cool down your entire house. But that is in effect what classic batch-processing fabs do. Fabs traditionally store in-process wafers in the ambient air of the facility. This means, that, to keep the wafers free of contamination – so critical at such small line widths – fabs must try to keep the entire plant, including the workers who inhabit it, hyper-clean. Quite apart from the cost and difficulties of such cleanliness, even hyper-clean air can cause problems: since inventories must queue up in ambient air waiting their turn for various batch processes, oxygen can attack and oxidize the wafers, producing a "black silicon" that can reduce yield.[9] Other process sequences are sensitive to moisture in the atmosphere. The effects of atmospheric degradation become increasingly significant as line widths get smaller. In addition, WIP inventories are subject to other kinds of oxidations, to polymer deformation of resists, and to ordinary dust contamination and handling breakage.

---

[8] A micron is a thousandth of a millimeter. Finer line widths allow more dense packing of a chip. Line widths of 20 microns were typical in the early 1970s, falling to 2 to 4 microns in the mid 80s, and to less than one micron today. 4M DRAMS have line widths of around 0.8 microns, 16M DRAMs require line widths of about 0.5 microns, and 64M DRAMs require widths of 0.33 microns or less. Technology now coming on line will process 300mm (12-inch) wafers with line widths less than 0.25 microns. Intel's new D1C fab in Oregon produces 300-mm wafers using 0.13 micron technology.

[9] Yield – perhaps the most important parameter in semiconductor fabrication – is the fraction of total chips processed that actually work.

With a single-wafer system, by contrast, one can more easily integrate or cluster together sequential process steps within a controlled atmosphere. In effect, a single-wafer system cools the milk carton in a refrigerator (or a series of refrigerators). This helps to eliminate cleaning steps that would otherwise be necessary if the wafers were exposed to air between steps. Moreover, large batch tools, such as diffusion furnaces, cannot maintain uniformity of temperature and other parameters across all the wafers in the batch, a problem that becomes increasingly important as line widths diminish. By processing only one wafer in a chamber at a time, single-wafer tools can achieve much greater process uniformity.[10] Most importantly, many process steps simply require extremely tight atmospheric control. Prominent among these are dielectric planarization, the smoothing of certain layers on the chip, and intermetal connection, the tricky business of making electrical contacts among the various levels of circuitry in a chip.[11] As line widths shrink, however, more and more stages will require the kind of atmospheric control that only a single-wafer system can provide.

---

10 Actually, it isn't necessary to process only one wafer in a chamber at a time. So-called semi-batch systems can also achieve high uniformity with a continuous-throughput system that processes several wafers at a time. The Novellus Concept One, for example, is a CVD tool with a lazy susan holding seven wafers (see Figure 2). It is ultimately a single-wafer system, however, as the wafers are fed in and removed one at a time. Each wafer is exposed to one-seventh of the deposition process at each turn of the carousel, in effect increasing uniformity by averaging.

11 One normally thinks of a simple integrated circuit as like a microscopic printed-circuit board of great complexity. In fact, the most complicated modern chips are like several distinct printed-circuit boards sandwiched together and connected in appropriate places by metal plugs. The microprocessors produced at Intel's D1C fab in Oregon require six layers of copper metalization.

Another benefit of single-wafer processing is the ease with which the wafers can be monitored and tested in real time rather than at discrete testing steps. In Shoshana Zuboff's (1988) famous phrase, single-wafer systems are more easily "informated." Monitoring provides a steady stream of data for operators to use in detecting problems quickly and for process engineers to use in uncovering bottlenecks and fine-tuning the system. This includes improved manufacturing-process documentation and more reliable "recipe downloading," the process of programming process steps. Moreover, the real-time aspect of the data makes it possible to engage in closed-loop control, that is, to test and adjust the process as it is happening rather than to wait until a step is finished, test, and then adjust subsequent runs. In the long run, the single-wafer approach thus leads more easily to overall factory simulation, including linking to computer-aided design and engineering.

Perhaps the most important benefit of single-wafer processing, however, is reduced cycle time. Cycle time is the time from when the blank wafers enter the production system to when the completed wafers emerge and are ready for assembly and packaging. In a batch system, output rates may be high, but so is cycle time. Instead of thinking about refrigerators, think now about dishwashers, and consider the problem of washing a kitchen-full of dirty dishes. Using a dishwasher is a batch process; washing by hand is a continuous process. Loading the dishwasher may ultimately have a larger "throughput," but the first clean plate reaches the cupboard more quickly with hand-washing. Batch semiconductor processing is like running dishes sequentially through many different dishwashers with many different capacities. This creates a queuing problem, and the wafers must often sit around in WIP inventories while waiting to form a batch of the appropriate size for the next process step. By contrast, single-wafer systems push only a single wafer through at a time (putting aside parallel processing steps), but the progress of that single wafer is not slowed as much waiting for other wafers to be ready.[12]

[12] In addition to reduced queuing time, single-wafer systems can also speed throughput because it simply takes less time to process a single wafer than it does a batch of wafers. This is so for physical reasons: it takes more time to heat up or cool down a large batch than a single wafer, for example. A single-wafer system may also be more easily controlled in a number of respects. This means that the wafer spends less time in the machinery, an important source of lower cycle time. A related benefit of reduced cycle time is the potential for faster learning by doing, since it permits production engineers to see more quickly the full effect on a wafer of all the process steps and allows them to adjust the process for all subsequent wafers (rather than for subsequent *batches* of wafers).

Faster cycle time means that the first chips get to market more quickly, which can significantly affect ultimate demand by making it more likely that engineers will choose the chip in a systems design. Even for standardized chips like DRAMs, lower cycle time is important because profits are highest earlier in the product life-cycle. But the flexibility of single-wafer processing becomes especially important for specialized and customized chips, production runs of

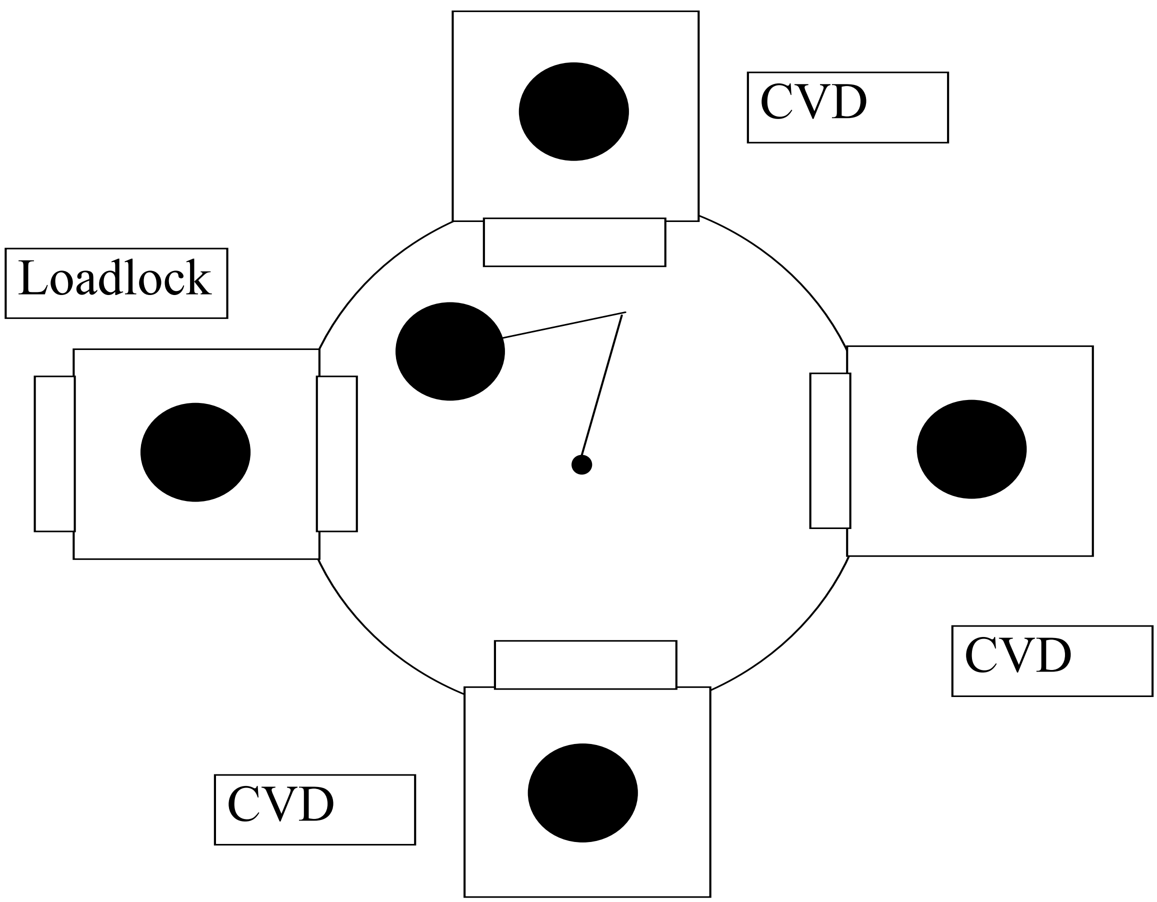

Figure 1. A parallel-processing configuration.

which may not be large enough to justify the set-up costs of batch processing. Lately, a number of industry observers, including strategy guru Clayton Christensen (Bass and Christensen 2002), have begun predicting the "demise" of Moore's Law. This famous dictum, named after Intel co-founder Gordon Moore, predicts that circuit density will continue to double every 18-24 months (Langlois 2002, p.) without increasing production cost, thus yielding an exponential growth in chip performance. Christensen argues that Moore's Law has lately begun to generate such an embarrassment of riches that users are increasingly unable to take advantage of available chip performance. As a result, competition will inevitably move away from the race for higher densities toward customization and speed to market. This in turn will accelerate the transition from batch to single-wafer processing.

Introducing a single-wafer step into a batch fab instantly creates a bottleneck, of course, since throughput of the fab is limited to the throughput of the single-wafer step. The obvious answer is to replicate the bottleneck stage in a parallel-processing configuration. The need for parallel processing was the original motivation for common-platform "cluster" tools. (See Figure 1.) Rather than having, say, four separate stand-alone process chambers, each with its own separate wafer loading and unloading facilities, one could mount the four chambers on a common platform and use a common robotic wafer-handling mechanism to move wafers to and from the various chambers and input-output

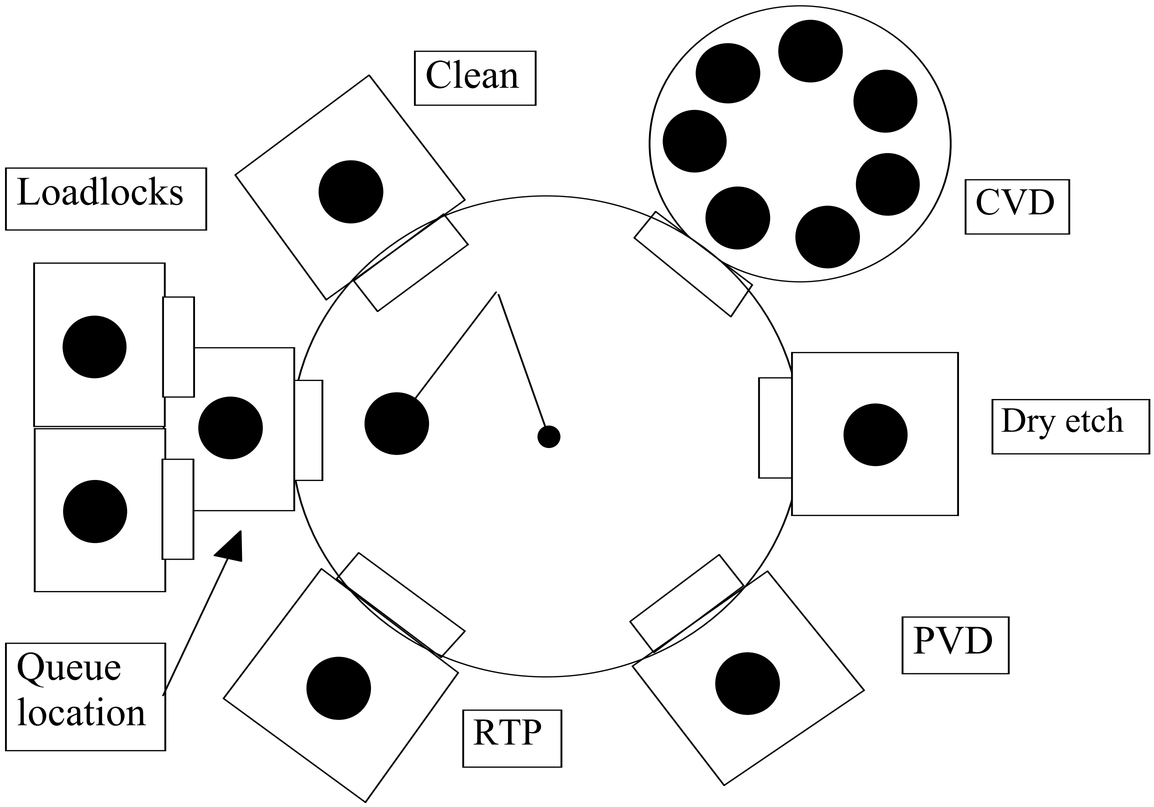

Figure 2. A hypothetical modular integrated-processing system. (After Burggraaf 1989.)

loadlocks. From the common-platform configuration, however, it becomes an easy step to serial rather than parallel processing. Instead of running the same process in all four chambers, one could instead run different processes, using the wafer handler to move the wafers from one to the other within a controlled atmosphere. This was the genesis of the integrated cluster tool (see Figure 2), which represents a genuine move in the direction of single-wafer processing.[13] The parallel configuration offers the benefit of redundancy, and can generate higher throughput when downtime is an issue; but as tools become more reliable, the serial configuration – which boasts superior cycles times – gains the advantage (López and Wood 2003).

Capabilities, organization, and standards.

The clustering of modules on a single platform implies the integration of distinct tools, each requiring a distinct set of design and manufacturing competences. This is even true of parallel clusters, since making a robotic wafer-handler requires competences different from those needed for the modules. But the integration of distinct competences is especially important in the case of serial clusters. One way to marshal the necessary capabilities is within the boundaries of a single firm large enough to possess and wield all, or at least most of, the competences necessary to produce a cluster tool. Another way is somehow to organize and integrate through contract the competences of a number of distinct firms. The American semiconductor equipment industry uses both of these approaches simultaneously.

---

[13] In the limit, indeed, independent modules for all fabrication steps could be linked and combined so that, in principle, the wafer never leaves the controlled internal environment of the system. All the modules would be tied together in a computer network, providing a real-time database for monitoring and engineering improvement. This is the ultimate vision of single-wafer processing, what some call the "pipeline fab."

Applied Materials is of course the preeminent example of a firm that tries to integrate a wide array of competences within a single organization. Interestingly, however, Applied's success reflects an initial strategy of *narrowing* its business focus and reducing its portfolio of products.[14] Michael McNeilly founded the company in 1967 to supply equipment to the nascent semiconductor manufacturing industry. Applied went public in 1972, and McNeilly quickly diversified into a variety of ventures that even included the purchase of a maker of silicon wafers.[15] But the recession of 1975 saw profits turn into losses, and the Applied board ousted McNeilly in favor of a venture capitalist called James Morgan. Morgan promptly jettisoned non-core businesses and reoriented the company back to semiconductor process equipment. Applied weathered the Japanese invasion, and even prospered by an aggressive entry into the Japanese and other international markets (Morgan and Morgan 1991).

In the 1980s, Applied placed another major strategic bet. At a time when batch processing ruled semiconductor production, Morgan and his colleagues chose to focus Applied's product development efforts exclusively on single-wafer technology. In 1987, the company introduced its first cluster tool, the

[14] This paragraph draws on Kinni (2002, p. 27-42).

[15] In many respects, the menu of diversification alternatives facing Applied in the 1970s was not unlike that facing the manufacturing sector. Because of the rapid growth of the industry attendant on the development of the planar process and the integrated circuit, American firms enjoyed so many profitable product opportunities that they became vulnerable to a focused attack by the Japanese, who entered with a narrower range of products and strong capabilities in volume production (Langlois and Steinmueller 1999).

Precision 5000, which has been touted as the most successful product introduction in the history of the business. The Precision platform was originally offered as a parallel-processing CVD tool; but within two years, chambers for etch and tungsten processes became available, opening the door to serial configuration. In 1990, the company rolled out another platform, called Endura, built around sputtering (PVD) processes, but later upgraded to include CVD, etch, and RTP modules (InfoNet 1994b, p. 5-10).

Thus, although Applied's capabilities are focused on mid-process cluster tools, the increasing variety of technologies that can be clustered in sequence means that Applied is necessarily widening its technological and product capabilities. In principle, of course, a maker of cluster tools could contract with outside concerns for the development of some of the modules. In the limit, a firm could outsource the design of all the modules and simply act as a systems integrator. Applied has quite deliberately chosen the opposite strategy – to develop internally capabilities in all areas of semiconductor fabrication technology. Initially, Applied did contract with firms like Peak Systems for an RTP module and GaSonics (since acquired by Novellus) for a photoresist stripping module. Both of these arrangements generated contractual problems and were abandoned.[16]

[16] In the case of Peak, the result was a $420,000 judgment against Applied Materials for breach of contract and misappropriation of trade secrets (*Peak Sys., Inc. v. Applied Materials, Inc.*, No. 707566 (Cal. Super. Ct. December 1, 1993)).

The difficulty of using outside suppliers for modules arose in part from the fact that Applied's cluster-tool platforms were and are closed proprietary systems. The chambers reside on a central platform or "mainframe" and are linked by a centralized control and communications architecture that uses a closed proprietary standard. This means that the investments that firms like Peak and GaSonics would have had to make in adapting their technology to Applied's mainframe would have been specific to transactions with Applied – the modules, and the knowledge investments they represent, couldn't be "reused" in transactions with other buyers.[17]

By contrast, modular cluster tools — or simply modular tools — comprise self-contained "smart" modules, each possessing its own computer and its own piping. The modules are tied together not by a central controller but by a set of open interconnect and control standards. The modules conform to a mechanical interface standard, which governs the placement and dimensions of the modules and handlers, and to various communications standards, which govern the way the decentralized computers talk to each other over a network. In the case of

[17] A follower of Williamson (1985) would be tempted to assert at this point that Applied's strategy of internal development as a whole was no doubt motivated by such problems of "contractual hazards" and "hold-up" in the face of transaction-specific knowledge and irreversible investments. And, as we will see, the SEMI/MESC cluster tools standards to which Applied's competitors adhere were motivated in part to reduce contractual costs by reducing the transaction specificity of a firm's development of a module. In this case, however, the court agreed with Peak's contention that Applied was secretly developing its own RTP technology all along and was using its contract with Peak to gain knowledge to speed that internal development. Contractual hazards were arguably more the *result* of Applied's strategy than the cause.

cluster tools, such an approach is not hypothetical. Most makers of cluster tools – apart from Applied – adhere in whole or in part to the so-called SEMI/MESC standards, which are promulgated by the Modular Equipment Standards Committee (MESC) of Semiconductor Equipment and Materials International (SEMI), the industry trade association.

The emergence of standards.

The process by which standards emerged in the cluster tool industry is rather different from those of well-documented cases like the QWERTY keyboard (David 1985; Liebowitz and Margolis 1990), the VHS videocassette recorder (Cusumano, *et al.* 1992), the IBM-compatible personal computer (Langlois 1992), or the 33-rpm LP record (Robertson and Langlois 1992). In all of those cases, standards emerged through a competition or "battle of the standards" among alternatives originally offered as proprietary schemes. In cluster tools, however, a single standard emerged immediately out of collective action within a fragmented industry.[18]

---

[18] A better historical analogy for the MESA/MESC standards might be the efforts of the Society of Automotive Engineers, led at first by Howard E. Coffin of the Hudson Motor Car Company, to standardize numerous parts used in the early automobile industry (Epstein 1928, pp. 41-3). Between 1910 and 1920, the S.A.E. reduced the number of types of steel tubing from 1,600 to 210 and the number of standards of lock washer from 800 to 16. Throughout the initial period of standardization, until the early 1920s, most interest was shown by the smaller firms, who had the most to gain. The larger firms such as Ford, Studebaker, Dodge, Willys-Overland, and General Motors tended to ignore the S.A.E. and relied instead on internally established standards. (Thompson 1954, pp. 1-11). In fact, something similar has happened in cluster tools in the wake of standardization. Before the development of standards, all tools used their own idiosyncratic valve designs. Outside

The story begins in 1989.[19] Commercial cluster tools had been on the market for only two or three years, but a number of firms, each considerably smaller than Applied Materials, were either in the market or planning to enter (Burggraaf 1989). In March 1989, a group of representatives from several Bay Area companies congregated at a motel in Fremont to begin what would become a rapid-fire series of meetings. Present at the first meeting were representatives of 11 companies, including the CEOs of four of those companies. In many ways, the cooperation among these firms was a startling change from the individualist go-it-alone culture supposedly characteristic of the industry. From another point of view, however, the cooperation was made possible precisely by the cultural network of Silicon Valley and its web of personal contacts among engineers and marketers in many distinct firms. Clearly, however, what catalyzed collective action was the threat of competition from Applied Materials. Apart from Applied, the cluster tool industry consisted of firms whose capabilities were limited, and not even the largest of these was able to offer a multiple-module tool

suppliers would craft each valve to the user's specifications. The dominant firm in the business is VAT of Liechtenstein, which is noted for the quality of its product. Since the promulgation of standards, however, a standard valve has emerged, making valves more a commodity and less a specialty item. American firms like High Vacuum Apparatus (HVA) and MDC Vacuum Products have begun to take business away from VAT, and valve prices have fallen dramatically. Another area in which standardization is lowering costs is software. With the development of communications and control standards, an increasing number of aspects of the control software can be handled by standard packages provided by firms like Thesis, GW Systems, Realtime Performance, and Techware Systems.

[19] This account of the standard-setting process follows Langlois (2000).

on its own. In the end, these firms had to rely on coordination across firm boundaries, and standards would help facilitate such coordination.

The *ad hoc* group called their would-be standard the Modular Equipment Standards Architecture (MESA). They put forward this mission statement: "Develop technically sound, common, non-proprietary interface standards which the U.S. equipment industry can utilize to individually and collectively offer the best available choice of automated, interchangeable, integrated tools."[20] The group worked feverishly over the ensuing weeks to develop a draft standard. The first goal was to standardize the mechanical interface of future cluster tools, that is, the physical connection between the wafer handler and the modules. This included such parameters as the size and shape of the port and the valve flanges, their height above the floor, and the reach of the robot arm.

---

20 Talking paper by Jeffrey C. Benzing of Novellus for the Sematech workshop on cluster tools, May 2, 1989.

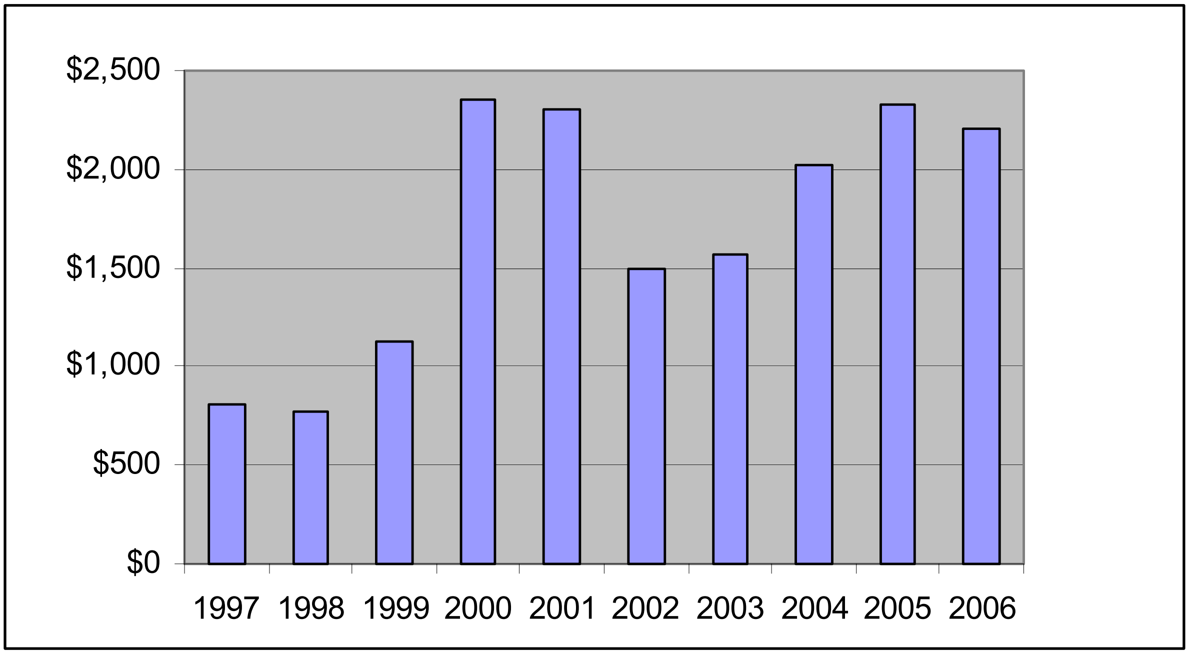

Figure 3. Modular cluster tool market, actual and forecast, millions of nominal dollars. (**Source**: The Information Network.)

Although invited, Applied Materials did not participate in the standard-setting process. Indeed, at one point Applied suggested its own Precision 5000 as an alternative standard, a proposal that was never taken seriously for technical as well as competitive reasons – the precision 5000 was not a suitably modular design. In the end, however, MESA and Applied were united formally when, at a meeting in September 1989, the MESA group voted to join SEMI, becoming reconstituted as MESC.[21] As a member of SEMI, Applied was effectively a member of MESC and eligible to vote on proposed standards.[22]

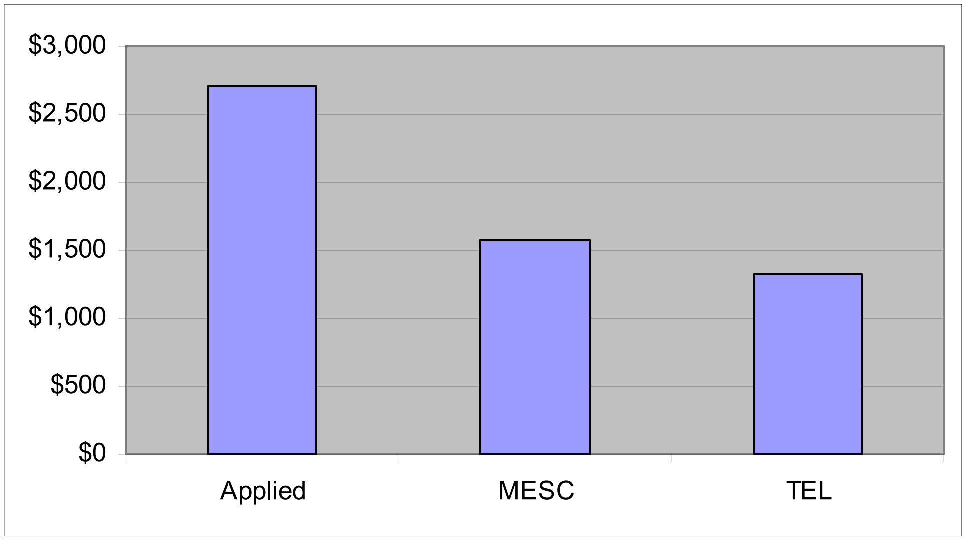

Figure 4. Standards adherents as a competitor to Applied Materials, 2003. (Cluster tool sales in millions of dollars.)
Source: The Information Network.

Competing development paths.

Rather than a battle of the standards, the current situation might best be thought of as a battle of alternative development paths: the closed system of Applied Materials, with its significant internal economies of scale and scope, and the open modular system of the competitive fringe, driven by external economies of standardization. The latter has grown to be a significant force: the market for

21 Among the principal motivations for joining SEMI was a fear of antitrust litigation, perhaps instigated by Applied (Langlois 2000).

22 And when the MESC mechanical interface standard eventually came to a vote in June 1990, Applied voted against it (Winkler 1990).

modular tools was over $1.5 billion in 2003 (see Figure 3), and the two largest SEMI/MESC vendors, Novellus and Lam Research, were the ninth and eleventh largest semiconductor equipment firms in the world in that year (Table 2).[23] This may seem like small potatoes, given that the market for non-modular cluster tools was some $7.8 billion in 2003 (InfoNet 2004b, p. 9-16). But that figure is somewhat misleading. Much of the lithography stage is now performed using cluster tools, but these are atmospheric tools (that is, tools for processes not involving vacuum or a controlled atmosphere) for which there exist no SEMI/MESC standards. If we look only at mid-process technology, Applied is still the clear leader, but the competition seems more real. As Figure 4 suggests, if we consider the entire SEMI/MESC network a competitor to Applied Materials, then the modular approach comes in second, ahead of Tokyo Electron. Moreover, if we look at specific submarkets, it appear that much of Applied's overall dominance comes from competing seriously in almost all submarkets, not necessarily from dominating all those submarkets (Table 3). For the moment, then, both development paths seem to be surviving, and neither is obviously driving out the other.

---

23 In 2003, Novellus had a 48.5 per cent share of the market for modular tools, and Lam a 33.2 per cent share (InfoNet 2004b, p. 9-14).

CVD		PVD		Etch		Ion implant		RTP	
Applied	54.5	Applied	84.3	Applied	26.5	Applied	23.9	Applied	45.3
Novellus	31.8	Novellus	7.8	TEL	35.7	Varian	34.5	TEL	29.4
ASM Intl.	8.3	Ulvac	5.9	Lam	29.7	Axcellis	36.1	ASM Intl.	9.3
Others	5.4	Others	2.1	Others	8.0	Nissin	5.5	Others	16.0

Table 3: 2003 market share in submarkets (percent)
Source: The Information Network (2004a)

Why? Let us pause to think about the basic economics of closed proprietary systems versus open modular ones. The primary benefits of a closed system lie in the ease of systemic coordination and reorganization. When the nature of the connections among the elements in a system are changing or idiosyncratic to applications, a unified organization can more cheaply coordinate and fine tune the connections. The value of such systemic coordination depends on both technological and demand factors. In some respects, and in some technologies, the value of idiosyncratic systemic coordination may be exogenous. In the automobile industry, for example, some degree of "integrality" may be inherent in the nature of the product (Helper and MacDuffie 2002, p.). Moreover, as Christensen and his coauthors have argued, an integrated organization is better able to fine-tune product characteristics to achieve greater functionality in an environment in which users eagerly demand such functionality (Christensen, Verlinden, and Westerman 2002).

On the other side of the ledger, an open modular system can more effectively direct capabilities toward improving the modules themselves (Langlois and Robertson 1992). Such a system harnesses the division of labor and the division of knowledge, allowing organizational units to focus narrowly and thus deeply; at the same time, it magnifies the number of potential module innovators, and thus can often take advantage of capabilities well beyond those even a large unitary organization could marshal. In this way, an open modular system "breaks the boundaries of the firm." There are both static and dynamic benefits. At any point in time, a user can "mix and match" components from a wider variety of sources to fine-tune the system to his or her taste, and thus reach a higher level of utility or tailored functionality than pre-packaged systems could offer. In the semiconductor equipment industry, this is called "best of breed." A user might mix a CVD module from manufacturer A with an etch module from manufacturer B and a wafer handler from manufacturer C, all assembled and guaranteed by system integrator D, who might add in some off-the-shelf components like valves and controller software. If, however, manufacturer E produces a CVD module that is innovative or otherwise superior in the eyes of the user, that module could replace module A in the package. In this way, the user doesn't have to rely on the capabilities of any single firm, which may not be on the cutting edge in all technologies.

More important, perhaps, are the dynamic benefits. Over time, an open modular system can lead to rapid trial-and-error learning and thus evolve faster than a closed system. Note that, at least in principle, this effect can counter the functionality benefits Christensen claims for the closed systems of integrated organizations. It is certainly plausible, if not logically necessary, that a capable integrated producer could achieve greater functionality by tweaking the system architecture than one could have achieved by picking even the best available assortment of modular components within a fixed architecture. But if the components of the open system evolve rapidly enough, an open system can leave yesterday's best integrated system in the dust. This was certainly the case in personal computers. The IBM PC of 1981 was a modular system that contemporary observers considered well below the level of functionality of other (mostly closed) systems. But PC components improved so rapidly that generic PCs eventually began to outperform even special-purpose minicomputers and workstations. The importance of this effect will depend on the number of potential component innovators, which in turn will depend on the extent of the market.

My working hypothesis is that, in the cluster-tool world, the forces favoring integrality and those favoring modularity are relatively balanced – for the moment, at least.

Applied Materials benefits from a certain degree of "integrality" inherent in the process of semiconductor fabrication. A fab is a tightly integrated and balanced system, one requiring the integration of knowledge between the manufacturer and the equipment supplier (Weber 2002). In effect, then, the equipment maker must supply not only the equipment itself but also "bundled" information and guaranteeing functions. A tool must fit in with a user's production line, and it must work properly and consistently. When it fails to work, it must be fixed promptly; moreover, the user must be confident that it will indeed be fixed promptly. And the user and the supplier must communicate information to ensure the continued refinement and improvement of the technology.

A large firm with significant internal capabilities can provide these ancillary services. Such a firm possesses not only the majority of skills necessary to fabricate the machinery it sells, it also possesses complementary capabilities in repair and customer service, including the ability to gather information to improve the product. Reputation is another important complementary asset, since it provides a guarantee to customers that promised ancillary services, especially on-site repair, will be reliably provided. In this respect, a modular system provided by a network of firms would seem to be at a disadvantage. If the modular approach is to succeed, the role of the system integrator is crucial.

A system integrator is an organization that packages the products of a number of suppliers — chambers, wafer handler, etc. — and provides the necessary ancillary services, including the guaranteeing function. In the absence of standards, the job of the system integrator as coordinator would be more difficult, and working with others would require the sharing of proprietary information in a way that could generate greater transaction costs. With standards, however, much of the necessary coordination is embodied in the standards, and the spillover of proprietary knowledge from one firm to another is minimized. This would increase the chance that the system-integration function could be provided through the market. The integrator would work with the customer to tailor a system; would work with suppliers (itself probably included) to produce the system; and would provide the necessary service guarantees. This means that the integrator would need to have a reputation of value significant enough to act as a hostage (Williamson 1985). In the parlance of the industry, this is called taking ownership of the system.

In the SEMI/MESC world, it is often a lead equipment maker who acts as system integrator. And, in practice, this usually means Novellus or Lam. In addition, users – manufacturers themselves – are often effectively the systems integrators. This is especially true of large, highly capable firms like Texas

Instruments and IBM. What has not happened, however, is the rise of independent third-party systems integrators, a development some had hoped for early on.[24]

So far, then, the need for close coordination with manufacturers, as well as the often idiosyncratic problems of fine tuning in the fab, have limited the advantages of standards in cluster tools – relative, at least, to those in, say, personal computers or software, where the benefits of modular innovation have wildly outstripped those of systemic integration.

Growth in the extent of the market brings with it experience that can increase internal capabilities, and thus the scope of the firm, in the manner Edith Penrose (1959) suggested. As in the case of the personal computer (Langlois 1992), industry-wide open standards in cluster tools emerged in a low-capability environment – few firms were capable of producing a complex system without help from others. Rochester-based CVC Products (since acquired by Veeco) was one of the early leaders in the use of MESC standards to assemble cluster tools using very little of its own capabilities and relying on a panoply of vendors. In 1992, they announced a MESC-compatible tool integrating components from seven other companies. By 1994, however, the company had done so much internal development in hardware and software that it could offer a tool for

[24] One suggestion in the early days of standard-setting was that aerospace firms might take on the role of systems integration (Newboe 1990).

which it failed to provide only the wafer-handling robotics and the module controllers (InfoNet 2004b, p. 3-16). This sort of capability building went on within the larger players like Novellus and Lam as well.

At the same time, however, outsourcing has become the rule in the industry. A startling difference between Applied Materials and MESC-compatible competitors like Novellus and Lam is the extent to which the latter outsource the manufacture of the modules they do produce. In 2001, Lam was an integrated manufacturer with 4,300 employees in 13 buildings. Today it employs half as many workers in only four buildings (InfoNet 2004a, p. 4-3). In its 2003 10-K filing, Novellus puts it this way: "We do all system design, assembly and testing in-house, and outsource the manufacture of major subassemblies. This strategy allows us to minimize our fixed costs and capital expenditures and gives us the flexibility to increase capacity as needed. Outsourcing also allows us to focus on product differentiation through system design and quality control and helps to ensure that our subsystems incorporate the latest third-party technologies in robotics, gas panels and microcomputers."[25]

In part, outsourcing is a strategy to deal with the highly cyclical character of the industry. Applied may be large enough to weather downturns, but smaller firms adapt by transforming fixed into variable costs through outsourcing, which gives flexibility to *decrease* capacity as well as increase it.

[25] Novellus 2003 10-K filing, p. 9. See also Lam Research 2003 10-K filing, p. 6-7.

Nonetheless, such outsourcing is a general trend in industry driven by growth in the extent of the market (Langlois 2003). Indeed, it is in this sense that systems integration is emerging in the industry: not by independent third-parties appearing suddenly to coordinate among market participants but rather through integrated firms retaining – and even deepening – their capabilities in system design, service, and technological coordination, while hiving off manufacturing operations to more specialized firms (Pavitt 2003).

References.

Bass, Michael, and Clayton Christensen. 2002. "The Future of the Microprocessor Business," *IEEE Spectrum*, April, pp. 34-39.

Burggraaf, Peter. 1989. "Integrated Processing: the 1990s Trend," *Semiconductor International,* June, pp. 65-69.

Christensen, Clayton M., Matt Verlinden, and George Westerman. 2002. "Disruption, Disintegration, and the Dissipation of Differentiability," *Industrial and Corporate Change* **11**(5): 955-993.

Cusumano, Michael, Yiorgios Mylonadis, and Richard Rosenbloom. 1992. "Strategic Maneuvering and Mass-Market Dynamics: the Triumph of VHS over Beta," *Business History Review* **66**(1): 51-94 (Spring).

David, Paul A. 1985. "Clio and the Economics of QWERTY," *American Economic Review* **75**(2): 332-337.

Doering, Robert, and Yoshio Nishi. 2001. "Limits of Integrated-Circuit Manufacturing," *Proceedings of the IEEE* **89**(3): 375-393 (March).

Epstein, R. C. 1928. *The Automobile Industry: Its Economic and Commercial Development.* Chicago: A. W. Shaw.

Helper, Susan, and John Paul MacDuffie. 2002. "B2B and Modes of Exchange: Evolutionary and Transformative Effects," in Bruce Kogut, ed., *The Global Internet Economy*. Cambridge: MIT Press.

Ikeda, Shuji, Kazunori Nemoto, Michimasa Funabashi, Toshiyuki Uchino, Hirohiko Yamamoto, Noriyuki Yabuoshi, Yasushi Sasaki, Kazuhiro Komori, Norio Suzuki, Shinji Nishihara, Shunji Sasabe, and Atsuyoshi Koike. 2003. "Process Integration of Single-Wafer Technology in a 300-mm Fab, Realizing Drastic Cycle Time Reduction with High Yield and Excellent Reliability," *IEEE Transactions on Semiconductor Manufacturing* **16**(2): 102-110 (May).

The Information Network (InfoNet) 2004a. *Applied Materials: Competing for World Dominance*. New Tripoli, Pennsylvania: the Information Network.

The Information Network (InfoNet) 2004b. *Cluster Tools in IC Processing: Technology and Market Forecasts*. New Tripoli, Pennsylvania: the Information Network.

The Information Network (InfoNet) 2004c. *Semiconductor Factory Automation: Technology Issues and Market Forecasts*. New Tripoli, Pennsylvania: the Information Network.

Kinni, Theodore B. 2000. *Future Focus: How 21 Companies are Capturing 21st Century Success*. Milford, CT: Capstone Press.

Langlois, Richard N. 1992. "External Economies and Economic Progress: The Case of the Microcomputer Industry," *Business History Review* **66**(1): 1-50 (Spring).

Langlois, Richard N. 2000. "Capabilities and Vertical Disintegration in Process Technology: The Case of Semiconductor Fabrication Equipment," in Nicolai J. Foss and Paul L. Robertson, eds., *Resources, Technology, and Strategy*. London: Routledge, pp. 199-206.

Langlois, Richard N. 2002. "Digital Technology and Economic Growth: the History of Semiconductors and Computers," in Benn Steil, David Victor, and Richard R. Nelson, eds., *Technological Innovation and Economic Performance*. Princeton: Princeton University Press for the Council on Foreign Relations, pp. 265-284.

Langlois, Richard N. 2003. "The Vanishing Hand: The Changing Dynamics of Industrial Capitalism," *Industrial and Corporate Change* **12**(2): 351-385 (April).

Langlois, Richard N., and Paul L. Robertson. 1992. "Networks and Innovation in a Modular System: Lessons from the Microcomputer and Stereo Component Industries," *Research Policy* **21**(4): 297-313.

Langlois, Richard N., and Paul L. Robertson. 1995. *Firms, Markets, and Economic Change: A Dynamic Theory of Business Institutions.* London: Routledge.

Langlois, Richard N., and W. Edward Steinmueller. 1999. "The Evolution of Competitive Advantage in the Worldwide Semiconductor Industry, 1947-1996," in David C. Mowery and Richard R. Nelson, eds., *The Sources of Industrial Leadership*. New York: Cambridge University Press.

Liebowitz, S. J., and S. E. Margolis 1990. "The Fable of the Keys," *Journal of Law and Economics* **33**(1): 1-25 (April).

López, Marcel J., and Samuel C. Wood. 2003. "Systems of Multiple Cluster Tools: Configuration, Reliability, and Performance," *IEEE Transactions on Semiconductor Manufacturing* **16**(2): 170-178 (May).

Macher, Jeffery T., David C. Mowery, and D. A. Hodges. 1999. "Semiconductors," in *U.S. Industry in 2000: Studies in Competitive Performance*. Washington, D.C.: National Academy Press, pp. 245-28

Morgan, James C., and Jeffrey Morgan. 1991. *Cracking the Japanese Market*. New York: the Free Press.

National Advisory Committee on Semiconductors. 1990. *Preserving the Vital Base: America's Semiconductor Materials and Equipment Industry*. Washington, DC: Government Printing Office.

Newboe, Betty. 1990. "Cluster Tools: A Process Solution?" *Semiconductor International,* July, pp. 82-88.

Pavitt, Keith. 2003. "Specialization and Systems Integration: Where Manufacture and Services Still Meet," in Andrea Prencipe, Andrew Davies, and Michael Hobday, eds., *The Business of Systems Integration*. Oxford: Oxford University Press.

Penrose, Edith T. 1959. *The Theory of the Growth of the Firm*. Oxford: Basil Blackwell.

Robertson, Jack. 1991. "Sematech Refocusing for CIM, Software?" *Electronic News*, July 29.

Robertson, Paul L., and Richard N. Langlois. 1992. "Modularity, Innovation, and the Firm: the Case of Audio Components," in Frederick M. Scherer and Mark Perlman, eds., *Entrepreneurship, Technological Innovation, and Economic Growth: International Perspectives*. Ann Arbor: University of Michigan Press.

Schumpeter, Joseph A. 1942. *Capitalism, Socialism, and Democracy*. New York: Harper and Brothers. (Harper Colophon edition, 1976.)

Singh, Rajendra, Mohammed Fakhruddin, and Kelvin F. Poole. 2003. "The Impact of Single-Wafer Processing on Semiconductor Manufacturing," *IEEE Transactions on Semiconductor Manufacturing* **16**(2): 96-101 (May).

Stowsky, Jay S. 1989. "Weak Links, Strong Bonds: U. S.-Japanese Competition in Semiconductor Production Equipment," in Chalmers Johnson, Laura Tyson, and John Zysman, eds., *Politics and Productivity: The Real Story of Why Japan Works*. Cambridge: Ballinger.

Thompson, G. V. 1954. "Intercompany Technical Standardization in the Early American Automobile Industry," *Journal of Economic History* **24**: 1-20.

U. S. Department of Commerce. 1991. *National Security Assessment of the U. S. Semiconductor Wafer Processing Equipment Industry*. Office of Industrial Resource Administration, Bureau of Export Administration.

Weber, Charles. 2002. "Knowledge Transfer and the Limits to Profitability: An Empirical Study of Problem-Solving Practices in Semiconductor Manufacturing and Process Development," *IEEE Transactions on Semiconductor Manufacturing* **5**(4): 420-426 (November).

Williamson, Oliver E. 1985. *The Economic Institutions of Capitalism.* New York: The Free Press.

Winkler, Eric. 1990. "MESC Link for Cluster Tools Approved; Applied Votes No," *Electronic News*, June 4, p. 1.

Zuboff, Shoshana. 1988. *In the Age of the Smart Machine*. New York: Basic Books.