Capabilities and Vertical Disintegration in Process Technology: The Case of Semiconductor Fabrication Equipment.

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ABSTRACT

This paper presents a detailed case study of the cluster-tool segment of the American semiconductor-equipment industry. That industry has embarked upon a technological trajectory in which cluster-tool components (or modules) conform to a set of common interface standards. Cluster tools are thus becoming a *modular system* in the manner of an IBM-compatible personal computer or a stereo system. Such standards permit the sharing and reuse of technological capabilities, leading to what one might call *external economies of scope*. These reduce the need for and the benefits of large size and systemic coordination, permitting firms to concentrate their capabilities narrowly and deeply on a small range of components.

The paper outlines the theory of modular systems; discusses the economics of single-wafer processing in general and cluster tools in particular; recounts the history of standard-setting in the industry; and examines ongoing issues of strategy and market structure. One conclusion of this analysis is that standard-setting may in this case blunt the widely touted benefits of the “Japanese model” of manufacturer-supplier relations. The public knowledge contained in common interface standards serves as a partial substitute for the detailed coordination and long-term relationships that model holds to be the hallmark of Japanese firms, thus shifting advantage in the direction of a loose network of small vertically and laterally specialized firms.

Introduction.

Alfred Chandler's influential book *Scale and Scope* (1991) has added new weight to the Schumpeterian proposition that the large vertically integrated firm was at the vanguard of economic growth in the late nineteenth and early twentieth centuries (Schumpeter 1950, p. 82). A number of writers have taken the message of Schumpeter and Chandler to be that economic capabilities are always best created within the framework of large firms enjoying internal economies of scale and scope; as a consequence, industrial competitiveness depends crucially — and perhaps even exclusively — on fostering internal capabilities. For a time at least, this argument found special application in the arena of high technology, including semiconductors. Until recently, it was common to hear that the decentralized, entrepreneurial American industry ultimately would prove no match for the large firms of Asia, and that the United States must somehow consolidate and bolster the internal capabilities of its firms, with government help if necessary (Florida and Kenney 1990; Ferguson 1985, 1990).

There is certainly much wisdom in the Schumpeter-Chandler view, especially as an antidote to the naive adulation paid to the model of atomistic competition in neoclassical theory and policy. Nonetheless, there is reason to think that an overemphasis on the internal creation and management of economic capabilities can be equally unhealthy. Networks of decentralized firms, including those networks often derogated as “markets,” can also be repositories and generators of economic capabilities. To insist on vertical integration — or, for that matter, on agglomerations of small “flexibly specialized” producers (Piore and Sabel 1984; Best 1990) — as a universal prescription misses the subtlety and historical idiosyncrasy of industrial evolution (Langlois and Robertson 1995).

A crucial issue in the comparison among the institutions of industrial organization is the ability of those institutions to generate technological progress. At the risk of oversimplifying matters somewhat, we might say that the relative merits of firms and networks hinge on whether innovation is *systemic* or *autonomous* (Teece 1986). When innovation is systemic, there is reason to think that a firm-like structure will prove more conducive to rapid technological progress. This is so because systemic innovation requires simultaneous change in many different stages of production, and common ownership of complementary stages lowers the transaction costs of persuasion and coordination (Silver 1984; Langlois and Robertson 1995). By contrast, there is reason to think that networks — including archetypical "markets" as one extreme — may have advantages when innovation is *autonomous*, that is, when technological change in one stage of production can proceed without requiring corresponding changes in other parts of the system. In this case, the advantages of the firm in persuasion and coordination are outweighed by Smithian economies of specialization and by the ability of networks to access a larger and more diverse pool of relevant capabilities (Langlois 1992; Langlois and Robertson 1992).

But the systemic or autonomous nature of innovation is neither entirely exogenous nor driven solely by technology. The structure of organization helps shape the pattern of innovation, which in turn influences the subsequent structure of organization. In short, a theory of organizational structure is properly part of an evolutionary theory of social institutions (Langlois 1993). A clear manifestation of this is the importance of one particular kind of social institution — namely, standards — for both innovation and industrial structure.[1] In the absence of shared conventions to demarcate the boundaries between and standardize the connections among stages of production, autonomous innovation is costly. As a result, competitive advantage may go to organizations with significant internal capabilities for systemic innovation. This would imply competition among individualized pre-packaged entities — what we can call closed proprietary systems. Automobiles would be an example: each car manufacturer chooses the attributes

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[1] See, for example, Kindleberger (1983) on standards as a social institution.

of a car, assembles it, and offers it to the public as a package. If common standards do appear, however, products may become what Langlois and Robertson (1992) call *modular systems.* (Imagine being able cheaply to assemble an automobile at home from a catalogue of interchangeable bumpers, fenders, engines, etc.) In the case of a modular system, competition among prepackaged entities gives way to competition among the producers of compatible modular components. This tends to favor networks at the system level, even if the various modules themselves are (internally) closed proprietary systems produced by what may be vertically integrated firms. Prominent examples of modular systems are IBM-compatible personal computers and high-fidelity audio systems (Langlois and Robertson 1992; Robertson and Langlois 1992).

In view of the costs of collective action involved in the setting of standards, the frequent emergence of such standards suggests that modular systems can offer net benefits over the closed proprietary alternative. These benefits come on both the demand side and the supply side. One effect of standard “interfaces” among components is to lower the costs of assembly, both by lowering transaction costs and by reducing the optimal scale of the assembly function. As a result, assemblers (who may be the system users themselves in some cases) can more cheaply tailor a system to the user's exact requirements. On the supply side, modular systems can lower production costs by enlisting specialization in the cause of innovation. More importantly, modularity breaks the barrier of the boundaries of the firm, bringing to bear both a larger volume and a wider diversity of capabilities than even the largest of organizations could cheaply marshal.

We can think of the role of standards in terms of economies of scope. Following in the tradition of Edith Penrose (1959), Teece (1980, 1982) has argued that economies of scope arise when an organization has excess capabilities that can usefully be applied to activities similar to the ones in which it is all ready engaged. To the extent, for example, that a software firm reuses pieces of existing code in writing new packages, it partakes of *internal* economies of scope: it can write several programs more cheaply per program than could separate organizations that had to write each package from scratch (Cusumano 1991). Analogously, an open modular standard helps create *external* economies of scope. By making public a common way for the components to fit together, a modular standard allows many *distinct* organizations to "reuse" the same knowledge. Each organization can concentrate on changes that improve a component without having to reinvent other components or the architecture that connects them.[2] With such external scope economies, a collection of separate organizations can produce a system more cheaply than can a single organization that has to generate all the relevant capabilities internally. In software, some computer scientists are suggesting that object-oriented programming may lead to inter-firm reuse of code as an alternative to the internal scope economies of the "software factory" (Cox 1990).

Case study: semiconductor-fabrication equipment.

Overview.

The integrated circuit was very much an American invention, developed independently but simultaneously by researchers at Texas Instruments (TI) 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 1979, nine out of the top ten firms were American.

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 1989, 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 (dominated by Canon and Nikon), automatic test equipment, and assembly and packaging equipment.

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 suffers from excess “fragmentation” and insufficient vertical integration. In one of the few academic examinations of this industry, a study by the Berkeley Roundtable on the International Economy (BRIE) concluded that

1979		**1989**	
Company	**Sales**	**Company**	**Sales**
Fairchild TSG (US)	$114.4	Tokyo Electron Ltd (J)	$633.9
Perkin-Elmer (US)	101.2	Nikon (J)	582.2
Applied Materials (US)	54.1	Applied Materials (US)	523.3
GCA (US)	54.1	Advantest (J)	398.8
Teradyne (US)	53.4	Canon (J)	383.6
Varian (US)	50.8	General Signal-GCA (US)	353.7
Tektronix (US)	39.2	Varian (US)	335.0
Eaton (US)	37.7	Hitachi (J)	210.0
Kulicke and Soffa (US)	37.0	Teradyne (US)	199.9
Balzers A.G. (E)	33.7	ASM International (E)	168.8

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

Source: VLSI Research, cited in GAO (1990).

Table 1: Top 10 Semiconductor-equipment suppliers, 1979 and 1989.

> 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. American firms regained the lead in market share in semiconductors generally, albeit only slightly at first (Pollack 1992). This turnaround was propelled by the growth of the personal computer market, whose fundamental building block — the microprocessor — was an American strong suit (Langlois and Steinmueller 1998). American firms also increased their attention to manufacturing quality in response to the Japanese challenge. As the fortunes of the American semiconductor industry began to reverse themselves, and with the growth of non-Japanese production in Asian countries (notably Korea) that lack an indigenous equipment industry, the fortunes of the American equipment industry also began to turn up. By 1992, Applied Materials had overtaken its Japanese rivals to become the largest semiconductor-equipment firm in the world. (See Table 2.)

Company	**Sales**
Applied Materials (US)	

More significantly, American firms are strong in a technological approach that promises to become increasingly important as integrated circuits become more densely packed. The flexible-cluster-tool segment of the equipment market may grow from $359 million in 1995 to $1.44 billion in 2000 (Anonymous 1996). And long-run prospects may be even better: as I will suggest below, the modular cluster-tool concept may prove to be a technological trajectory ultimately applicable to the entire semiconductor production process.

If American firms do succeed in this developing market, it will be because they have indeed managed to develop “mechanisms to coordinate their learning and investment processes.” But, without minimizing the importance of improved cooperation among firms, those mechanisms may not involve significant increases in concentration or vertical integration. Cluster tools are rapidly becoming a modular system, driven by standards now emerging. And modular standards are a mechanism to coordinate learning without integration. Moreover, by reducing the minimum efficient scope of the firm — if I may make that analogy with the concept of minimum efficient scale — cluster-tool standards may also reduce the costs of miscoordinating investment, thereby moving the function of explicit coordination within the range of those mild forms of quasiintegration that come under the heading of "corporate partnering."

From batch to single-wafer processing.

In order to understand these trends, and the issues of modularity and standard-setting that attend them, one needs to look more closely at the semiconductor production process.[3] 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 100 wafers at a time. All high-volumes "fabs" — as semiconductor production lines are now invariably called — currently use batch techniques, and these have worked well through the current DRAM generations.

The alternative to batch processing is single-wafer processing. Instead of processing many wafers simultaneously, single-wafer systems 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.[4] Although years of learning currently place the overall economies squarely on the side of conventional batch, there are

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[3] A good basic reference on semiconductor fabrication is Van Zant (1990). For a brief discussion, see Langlois *et al*. (1988), pp. 13-16.

[4] 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.

advantages to single-wafer processing that are emerging and are likely to become increasingly significant as semiconductor line widths decrease below 0.5 microns.[5] These advantages fall under three headings:

- Reduced cycle time;
- Greater atmospheric control and uniformity; and
- The potential for real-time monitoring.

Cycle time is the time from when blank wafers enter the production system to when completed wafers emerge and are ready for assembly and packaging. In a batch system, output rates may be high, but so is cycle time. Consider the analogous 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 materially slowed waiting for other wafers to be ready. One of the advantages of single-wafer, then, is that chips suffer less degradation waiting in WIP inventories. Those inventories are stored in normal (albeit hyper-clean) atmosphere within

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[5] 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.

the clean room.[6] This allows oxygen to attack and oxidize the wafers, producing a "black silicon" that can reduce yield, the fraction of total chips processed that actually work. 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.

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. And, quite apart from problems of degradation, 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. Also, and perhaps most importantly, reduced cycle time means potentially 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).

The single-wafer approach also has benefits for atmospheric control that go beyond limiting degradation from waiting time in WIP queues. With a single-wafer system, one can more easily integrate or cluster together sequential process steps within a

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[6] There is an alternative for batch processing in which the wafers are stored in a controlled cassette environment using such gasses as nitrogen and argon instead of ambient atmosphere. These techniques are not in widespread use, however.

controlled atmosphere. 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.[7] A long-term benefit of single-wafer processing may be the ease with which the wafers can be monitored and tested in real time rather than at discrete testing steps. Such monitoring would provide 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 would include 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 may lead more easily to overall factory simulation, including linking to computer-aided design and engineering (CAD/CAE).

Many of these benefits remain on the horizon, of course. Single-wafer processing is a technological trajectory that, for some processes at least, arguably promises lower costs than batch processing in the long run, but which is not yet nearly as developed as the batch approach. Nonetheless, single-wafer tools are making inroads. Such tools have gotten their foot into the door of otherwise batch fabs by offering what people in the

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[7] 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. 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.

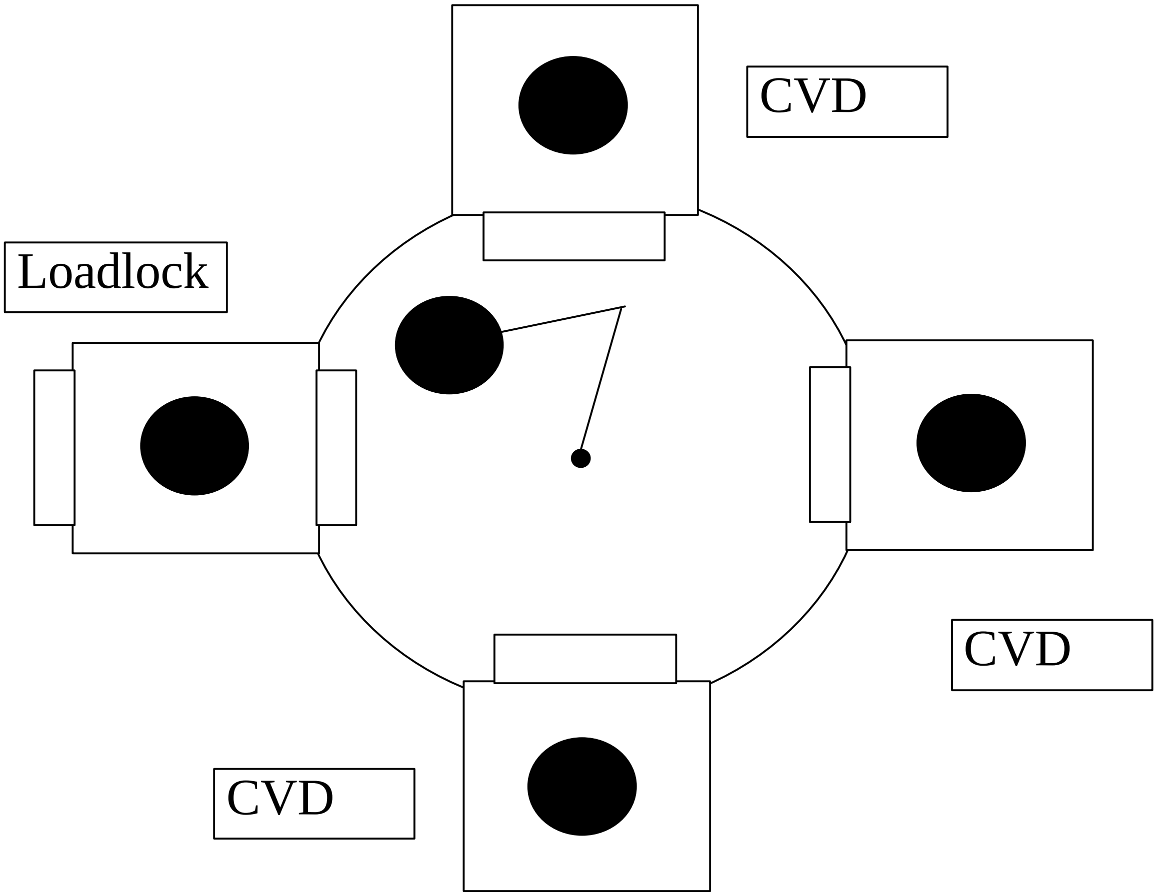

Figure 1. A parallel-processing configuration.

industry call an "enabling technology." That is, single-wafer tools are beginning to sell because they perform certain specific functions in the fab better than the alternatives. These functions are controlled-atmosphere steps, and today typically include 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.[8] These process functions are becoming increasingly important as chips become more sophisticated.

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[8] 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. A 32-bit microprocessor chip, for example, may have four such "metalization layers."

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 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 wafer-handling mechanism to move wafers to and from the various chambers and input-output loadlocks. Some early tools that took this approach were General Signal's Drytek Quad (1985) and Applied Materials' Precision 5000 (1987).

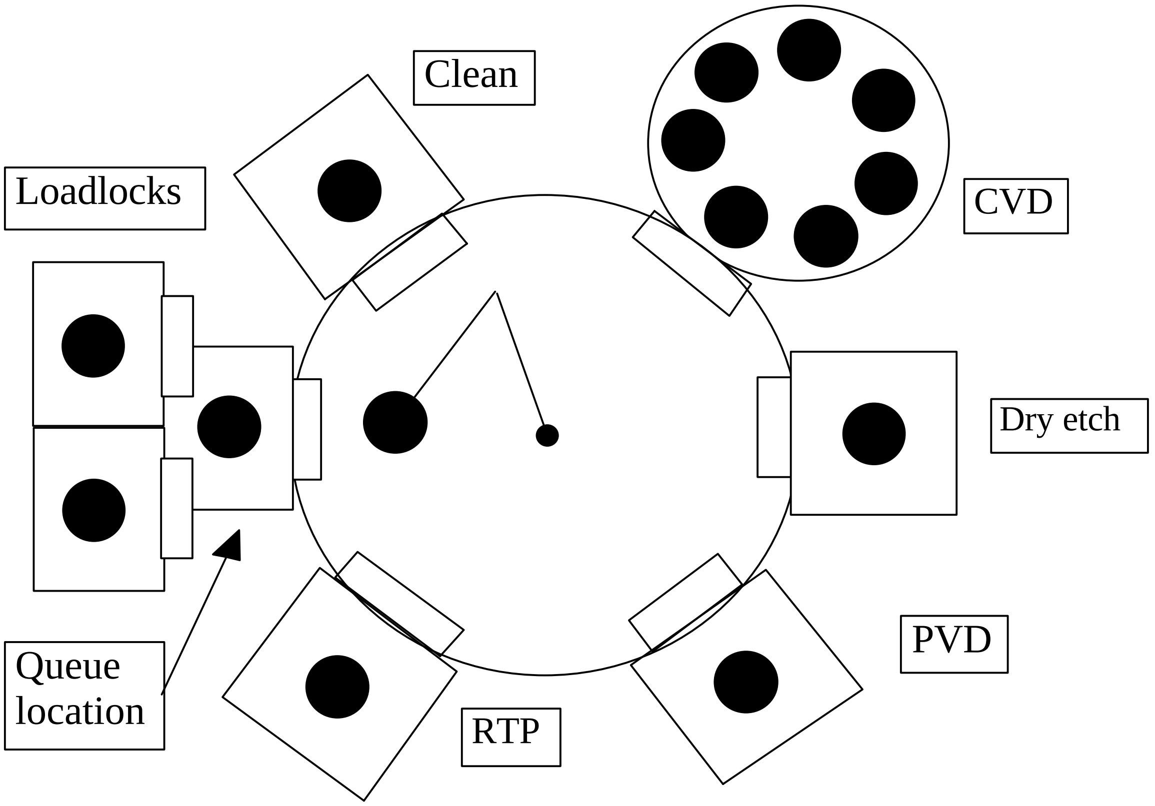

Figure 2. A hypothetical modular integrated-processing system.
(After Burggraaf 1989.)

From the common-platform configuration, however, it becomes an easy step to sequential 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.) Such tools also became enabling technologies in some areas, since they obviated removal of the wafers form the controlled atmosphere, preventing deterioration and eliminating cleaning steps. The Precision 5000 is an archetype of a successful cluster-tool platform. Of the 800-900 machines shipped by 1992, about 40 per cent were configured for integrated or sequential processing, with the remainder configured for parallel processing.[9]

The Drytek and Applied machines, among others, 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. Moreover, the chambers themselves are "dumb," relying on commands from the central controller. 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.

Modular tools represent an alternative not only to proprietary cluster tools but also, in the long run, to the concept of stand-alone tools within a normal-atmosphere clean room. Genuinely independent modules for all fabrication steps could be linked and

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[9] Interview with Peter Hanley, then of Applied Materials, March 12, 1992.

combined so that, in the limit, the wafer never leaves the controlled internal environment of the system. (Indeed, the modules need not be single chambers but could themselves be proprietary multichamber tools — so long as they conform to the standards in their dealings with the other modules.) 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.”

Although the ultimate vision is still far in the future, there have all ready been a number of efforts in its direction. By the early 1990s, Texas Instruments had constructed a complete single-wafer fab line on an experimental basis. The project, called the Manufacturing Management Science and Technology (MMST) program, was funded by the U.S. Air Force and the Defense Advanced Projects Research Agency (DARPA), which were anxious to make certain that American companies possessed all the capabilities necessary for flexible production lines to make a variety of low-volume chips for defense purposes (Iversen 1989). TI's mandate was to produce commercial equipment, even though the company did not want to get into the business of producing cluster tools (even for internal use) and would at most license some aspects of the technology.[10]

It does seem clear that the single-wafer approach is well suited to low-volume applications. A more difficult question is whether, when, and to what extent single-wafer approaches will be competitive for high-volume mass-production applications. It is significant in this light that IBM has apparently committed itself to the single-wafer approach in its 16M DRAM fab at Essex Junction, Vermont. The line clusters together lithography; dry etching; CVD and other “hot” processing; and deposition-etch sequences. These integrated stages are coupled by intelligent robots that transport the wafers among the “islands of automation.” IBM's explicit goals in taking the single-wafer approach are

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[10] Interview with Bob Doering of Texas Instruments, February 20, 1992. In 1994, TI did in fact license large portions of the MMST technology to CVC Products (Anonymous 1994).

to reduce the complexity of the production process and to decrease cycle time, thus speeding “process, circuit, and defect learning” (Bergendahl, *et al.* 1990). In most applications, however, it seems likely that a hybrid approach — mixing batch and single-wafer tools — will emerge and persist for some time.

The Economics of modular cluster tools.

The most forceful driver of cluster-tool adoption in the short term will be technical superiority, the role of such tools as an enabling technology. There are a number of potential areas in which cluster tools play this role. But perhaps the hottest growth area for such tools is in the deposition of Tungsten for intermetal connection, a procedure that requires the low temperatures and controlled atmosphere of a cluster tool (McLeod 1990; Winkler 1991). But this function can be accomplished by closed proprietary tools operating as isolated stations within a batch-processing environment. The speed with which genuinely modular cluster tools penetrate the market will depend on a number of factors.

- Economies of standardization and specialization.
- Flexibility.
- Reliability.
- Organizational issues.

Specialization and standardization.

One of the most prominent potential benefits of an open modular cluster-tool standard is the ability it offers users to mix and match components — process modules, wafer handlers, etc. — from different manufacturers in a way that takes advantage of the “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.[11]

Of course, one might list advantages to production within a single firm that possesses significant economies of scale and scope. Producing self-contained modules may require duplication of parts — piping, controllers, etc. — that could be shared on a closed system. Moreover, a dominant manufacturer of a closed proprietary system could conceivably overcome the disadvantages of having less-than-best-of-breed technology by producing at high volume, thus reducing costs and gaining learning-by-doing benefits. Indeed, critics of American manufacturing deride the U.S. penchant for cutting-edge technology as a fatal obsession. The Japanese semiconductor industry has succeeded despite a conservative approach that prefers refining existing techniques to trying out new technology.

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[11] It is not strictly true that a maker of a closed proprietary system cannot draw on external capabilities. For example, Applied Materials has had agreements with other firms to supply modules that “bolt on” to the Precision 5000. But the closed, centralized, and idiosyncratic character of the 5000 makes that sort of transaction more costly than in a world of standards. The parties to such an agreement must transfer far more knowledge to one another than would be necessary with an open modular standard. And some of that knowledge may be proprietary, leading to transaction costs of the hold-up variety popularized by Williamson (1985) and others. Moreover, a significant part of the knowledge generated by the bolt-on firm would be inapplicable to projects with other system manufacturers. Indeed, exactly this situation has arisen in the case of the Precision 5000. Peak Systems has sued Applied over a bolt-on system that the latter contracted for. Peak claims that Applied illegally appropriated Peak's technology and that they kept Peak's resources focused exclusively on Applied's proprietary platform, thus making it virtually impossible for Peak to serve other customers.

In the end, the matter is an empirical one. But there are a number of considerations that weigh in on the side of the modular approach. As I suggested above, one effect of common standards is to create external economies that have much the same benefits as the internal economies of a large firm. Ultimately, economies of scale and scope, whether internal or external, are typically economies of knowledge reuse.[12] In the case of modular systems, the existence of standards allows a component maker to use knowledge about other parts of the system without actually possessing that knowledge. By thus lowering the minimum efficient scope of the firm, a modular system encourages competition without duplication. That is, firms competing to supply the parts of a modular system need to generate a much smaller amount of overlapping non-innovative knowledge. An anecdote may convey the spirit of this idea. During the meetings to develop cluster-tool standards (on which see below), organizers conducted an informal poll of firms present to gauge which types of businesses were represented. When the participants were asked which of them represented robotics firms, nearly all raised their hands.[13] In the absence of standards, the separate competitors were all forced to generate their own internal capabilities in robotics, even though many if not most would have preferred to buy a wafer-handling system if one had been available cheaply. The availability of a compatible third-party wafer-handler is an external economy of scope that substitutes for the reusable internal capabilities in robotics that a firm might generate itself.

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[12] What makes it possible to produce the 200,000th of a particular model of car as cheaply as (or even more cheaply than) the 100,000th is that most of the knowledge used to produce number 100,000 — embedded in the machines, personnel, and organizational rules of the firm — can be reused to produce number 200,000. The same is true when the company produces a new model car: much of the knowledge gained on the old model can be reused on the new model. But we call the first case an economy of scale — in the sense of the learning curve if not in the strictly neoclassical sense — and the second case an economy of scope. For an elaboration of some of these ideas, see Langlois (1998).

[13] I am indebted to John Dunn for this story.

Lowering the minimum efficient scope of the firm can lower costs in two ways. First, the standardization of parts permits economies of scale in the production of those parts. A prime example of this is in the area of valves, which control the flow of gasses between chambers. Before the development of standards, all tools used their own idiosyncratic valve designs. Outside 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. This may not be the most important source of cost savings, however. A possibly more significant effect is the lowering of the costs of the modules, handlers, and other major parts. Even though these will not likely become commodities and will not likely be produced in volumes that will generate significant economies of mass production, increased competition among component makers will nonetheless tend to spur the search for cost economies.[14]

What about the internal scope economies of a centralized architecture? It seems very likely that such economies, if important at all, disappear very quickly with increasing system complexity. Cluster tools are becoming decentralized for much the same reasons that networks of personal computers and work stations are replacing mainframes and minicomputers: the rapidly decreasing costs of decentralized computing power. Indeed, at

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[14] Of course, competition will operate on the quality and product-innovation margins as well, which is just a way to restate the best-of-breed argument.

least one maker of modular cluster tools uses controllers for its modules that are essentially off-the-shelf IBM PC-compatible personal computers without keyboards and monitors. Moreover, there is reason to think that makers of closed proprietary systems would have switched to distributed architectures for their future tools even in the absence of a movement toward standards.

Furthermore, the best-of-breed argument can be extended from the initial configuration of the machine to *changes* in configuration over time. One of the benefits of a modular system is the ability to change components as the user's needs change or as component technology improves (Langlois and Robertson 1992). In the case of semiconductor fabrication equipment, user needs are driven by the obsolescence of the devices being produced. In the last few years, the lifecycle of leading-edge chips has fallen to two or three years. Producing a new generation of ICs in an existing fab means scrapping perfectly good production equipment. With a modular cluster-tool approach, however, one can keep parts of the system (the wafer handler at the very least and perhaps some of the modules) while scrapping only the obsolete modules. In this way, cluster tools extend the economic life of the user's capital equipment (McNab 1990). Even closed proprietary systems take a “platform” approach, in which common components serve as the basis for an upgradeable family of tools (Monkowski 1991). But a standardized modular approach would go beyond the proprietary platform, freeing users from the technological trajectory of any one company.

A related factor in favor of modular tools is the blurring of the line between prototype equipment and production equipment. When a user wants to adopt a new technology for some production step, it typically first tries the process on a demonstration or development line. If the new technology is to be adopted in a batch production line, however, the production model may have to be quite different from the test model, which would have been designed to produce only small sample batches. In a single-wafer system, the production model will be much closer to — or, in the limit, identical with — the test model, since both will have been designed for continuous processing rather than batch. Modularity makes the transition even easier, since both the test line and the production line would conform to the same standards. The modular approach thus eases the always-difficult transition from development lab to production line, which in turn speeds the rate of technological improvement.

Flexibility.

If modular tools allow the flexibility to change process technology cheaply when IC generations change, then it also arguably allows flexibility to change the production process cheaply for other reasons. For example, one might be able to switch a fab to the production of a different kind of chip by changing only a few modules. Even with a modular system, of course, such change can be costly. Production engineers insist on "qualifying" process tools, that is, subjecting them to a rigorous set of tests and measurements, before they can be put into service. Even bolting on a few new modules requires that the system be requalified, at least in part, and that takes time. But the process of changeover in a modular system is surely cheaper than making the equivalent change to a completely new dedicated tool set.

This flexibility effectively creates economies of scope at the level of IC production. The value of such economies will depend on the demand for standardized chips. Increasingly, fabs around the world cannot fully utilize capacity producing only DRAMs for a saturated market. Thus, there remain few lines that do not produce more than one kind of chip. For example, a DRAM line might also occasionally produce application-specific integrated circuits (ASICs), which require a quite different sequence of process steps. The smaller the production run, the greater the value of flexibility, an observation that underlies the widespread belief that cluster tools (and single-wafer systems in general) will find their earliest economical uses in low-volume specialty fabs. As I suggested above, the question is whether — or, more likely, when — the cost performance of single-wafer techniques will ultimately overtake that of batch techniques at high volumes.

Even if batch techniques continue their mass-production superiority for some time, the modular single-wafer approach may nevertheless become important by providing a flexible-manufacturing alternative (Steinmueller 1992). Whatever the ultimate shape of the cost curves at high output levels, it is clear that minimum efficient scale sets in much sooner for an IC producer using flexible single-wafer technology. This may make it economical to produce small volumes of specialized chips rather than large volumes of generic chips, effectively shifting competition in ICs to nonprice margins (where the American industry has always felt most comfortable) and away from the price margin (where the Americans have done less well).

An alternative to specialized chips is the ASIC, which is a generic logic chip that can be mass produced at low cost and then customized by the user in one of a number of ways. However, such chips perform less well than chips customized at the mask level (that is, chips customized from the start), and their range of application is limited. The success of the flexible-production alternative will depend on the cost-performance characteristics of customized chips (relative to ASICs) and on the cost-performance characteristics that chip users demand. Even though defense procurement, an important source of demand for high-performance, low-volume chips, is likely to diminish, the increasing sophistication of electronic equipment in general may be a favorable trend for the customized-chip business.

Reliability.

The making of semiconductor chips is a capital-intensive business. But unit costs per wafer are typically much more sensitive to factors like throughput, yield, and tool reliability than to the purchase price of the tool (Carnes and Su 1991). And reliability, in particular, has been a weakness of cluster-tool systems. Part of the disaffection for such devices in Japan and Korea evidently stems from unhappy experiences with unreliable tools in the past (Burggraaf 1991, p. 66).

In a continuous-throughput system, a breakdown in any link in the chain can shut down the whole line. If we think of a cluster as a linear sequence of process steps, then the reliability of the whole system goes up as the power of the number of linked steps. For a cluster to achieve 90 per cent reliability over some time interval, for example, each step of a six-step process would need a reliability of 98.3 per cent. At the same time, of course, the existence of parallel-processing steps would create redundancy. If a cluster contained two chambers running process A and one running process B (perhaps because process A takes twice as long as B), the system could limp along if one of the A chambers were to go down. Indeed, some have suggested that, in a modular system, a fab could have spare chambers waiting in the wings to replace a downed chamber; critics wonder, however, whether this would save much time, since the tool would have to be requalified even if the spare chamber had been tested off line (Newboe 1990, p. 86).

On the other side of the ledger, the economic costs of failure in a cluster module can be much smaller than the analogous costs in a stand-alone batch tool. A vertical furnace holding 100 wafers, each worth as much as $10,000 in potential microprocessor chips, puts $1 million at risk. By contrast, a malfunctioning cluster chamber risks only one wafer.

In the end, however, the reliability of cluster tools will depend on the quality of the product, as measured by the process results those tools achieve. As in other industries, the American semiconductor-equipment industry has been better at product development than at product reliability. Part of the reason for this has been the limited internal capabilities of many American firms. With the advent of standards, however, smaller firms will tend to specialize in particular technologies, allowing a kind of capability deepening. By producing, for example, only one specific module — rather than a module plus complementary technology — a company would be better able to "debug" its product and improve reliability.[15]

Organizational issues.

Economists have always understood, at least in principle, that the "product" a firm sells is not often just the unencumbered item that leaves the premises in a shipping crate. Even a manufacturer of a physical product is often ultimately the provider of a service, and the physical item is necessarily bundled with less-tangible informational and other services. This is certainly true in the case of semiconductor-manufacturing equipment. Here the bundled services include both information and a guaranteeing function. A manufacturing system 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. Applied Materials is the American prototype of such a firm, although other firms, like Lam Research and Novellus, come close. 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

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[15] This is the argument of G. Dan Hutcheson, president of VLSI Research, as quoted in Rice (1991).

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 system integrator would almost surely have to provide most of the technology itself, since working with others would require sharing of proprietary information in a way that could generate transaction costs. With standards, however, the spillover of proprietary knowledge from one firm to another is minimized. This would allow the system-integration function to 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).

The most likely possibility is that a lead equipment maker would act as system integrator. It would work with other manufacturers of similar size, but would alone provide the ultimate guarantees. In the parlance of the industry, this is called taking ownership of the system. In some cases, as in the ongoing collaboration between Novellus and Lam Research (Rice 1991; Holden 1992b), two similar-sized companies might team up and share ownership, so long as the customer can be made satisfied with the arrangement. In the semiconductor-equipment industry, as in many other American industries, such cooperative arrangements are becoming a pronounced trend. It is also conceivable that independent third parties might become integrators. Fearing that too much proprietary information would leak across even the anonymous boundaries of the standard architecture, at least one industry official suggested early on that aerospace companies might be appropriate candidates.[16] What seems to be happening, however, is that new companies will arise to fill the integrator role. One such is CVC Products, whose Connexion cluster tool offers the buyer a range of options, almost all from third-party vendors (Holden 1992a). Another possibility is that the users — the semiconductor manufacturers — might themselves act as system integrators. This is especially likely in the case of large users (like TI and IBM) that have substantial capabilities of their own in processing technology.

The emergence of standards.

The process by which standards are emerging 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. A standards battle did once threaten in the cluster-tool industry, and such a battle may yet take place. But the origins of the standards in this case were, if not exactly "spontaneous," then at least far more grass-roots and collaborative in character. The Modular Equipment Standards Architecture (MESA) was the result of the work of an *ad hoc* organization comprising the bulk of firms in the cluster-tool and related industries. The significant exception was Applied Materials, by far the largest firm in the business,

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[16] Bob Doering of Texas Instruments, quoted in Newboe (1990).

whose Precision 5000 platform briefly offered an alternative to MESA.[17] Quickly, however, the MESA committee was folded into Semiconductor Equipment and Materials International (SEMI), the equipment makers' trade group, becoming the Modular Equipment Standards Committee (MESC). Applied Materials is now a member, albeit somewhat grudgingly. And, although Applied Materials' strategy for its future tools is still unclear, it appears that MESC has indeed been established as *the* industry standard.

The story begins in 1989. 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). On March 30, 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,[18] including the CEOs of four of those companies.[19] 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

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[17] 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).

[18] AG Associates, Drytek, General Signal Corporation, General Signal Thinfilm Company (GSTC), Genus, Lam Research, Matrix, Novellus, Peak Systems, SSI, and Silicon Valley Group.

[19] Minutes of March 30, 1989 meeting. The CEOs were Ed Dohring of GSTC, Roger Emerick of Lam Research, Robert Graham of Novellus, and Tim Stultz of Peak.

marketers in many distinct firms. For example, General Signal Thinfilm Company was something of a cheerleader in the drive toward standards, having pushed the idea since early 1988 through informal discussions and "partnering" efforts with other vendors.[20]

The *ad hoc* group adopted the name MESA as its banner, and 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."[21] 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.

On May 2 and 3, 1989, Sematech held a technical workshop on cluster tools in Dallas, Texas. Part of Sematech's mission is to develop industry standards, which were on the agenda for this workshop. The MESA members who attended used the occasion to present the work they had been doing and to offer MESA as an industry standard. Applied Materials also had representatives at the meeting. Quickly, Applied responded to the MESA offer by proposing to "open up" the precision 5000 architecture as an alternative to MESA (Winkler 1989a). A battle of the standards appeared to be in the offing.

Applied's argument for adopting the Precision 5000 as a standard was that, with an installed base in 1989 of some 300 machines and 1,000 chambers, the 5000 represented

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[20] Private communication with John Dunn, June 8, 1992.

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

a proven technology (Morgan 1989). The MESA standards, Applied argued, were being created in the abstract rather than as a response to customer needs. Proponents of MESA argued back that a standard is necessarily abstract and conceptual, and that the members of the group were in any case bringing to bear a lot of collective experience with customers (Dunn 1989).

In Dallas, the MESA committee invited Applied to attend MESA meetings, specifically a congregation later in the month at Semicon West, one of the large industry trade shows that SEMI sponsors around the world. Applied declined, and suggested that it would not become involved in standard setting unless MESA were somehow brought under the umbrella of SEMI. The Semicon meeting attracted considerable attention from other equipment firms, who began joining MESA in large numbers. Sematech, which, as a quasi-governmental organization, could have affected the choice of standard by throwing its weight in either direction, chose neutrality instead (Winkler 1989b).

Ultimately, however, the threatened battle of the standards did not emerge. For one thing, MESA and Applied were quickly united institutionally when, at a meeting at Semicon East on September 12, 1989, the MESA group voted to join SEMI, becoming reconstituted as MESC. As a member of SEMI, Applied was effectively a member of MESC and eligible to vote on proposed standards.[22] There is also arguably a technical reason why a standards battle did not really emerged. Although the 5000's mechanical interface could in principle have served as a standard comparable to the MESC mechanical standard, the Applied machine is otherwise a closed, nonmodular system.[23] Since the goal

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[22] When the MESC mechanical interface standard eventually came to a vote in June 1990, Applied voted against it (Winkler 1990b). They cited technical reasons: that the robot's proposed size and reach would reduce reliability. MESC proponents dispute this.

[23] In fact, proponents of the MESA/MESC standards argue that even the 5000's mechanical interface would have been unsatisfactory for a standard, since the opening through which the wafer passes in

of MESA was total modularity, including a decentralized communications architecture, the 5000 could have been “opened up” only by being redesigned.

MESC has unquestionably become the standard of the non-Applied world. A large number of equipment vendors quickly began offering MESC-compatible systems or modules (Dorsch 1991b). The economic benefits of a standard for a network of small firms proved overwhelming, and Applied's machine was not a genuine alternative — for technical as well as strategic reasons. Moreover, some of the larger American users threw their weight behind MESC. Texas Instruments joined MESA in July 1989 (Winkler 1989c) and IBM is also said to be favorably disposed (Winkler 1990a).

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. So far, the market has chosen Applied over MESC, although the latter may be gaining ground. Lam Research, which made its mark in etching equipment before diversifying and which has adhered to MEC standards, is now the fourth largest semiconductor-equipment firm in the world (see Table 2).

The interesting choices will arise when fabs begin the move to twelve-inch (300 mm) wafers in the next few years.[24] Because of the larger wafer size, the physical dimensions of the mechanical interface — both MESC and Applied's — will have to change. Applied has several options in designing its 300 mm cluster tools. In 1994, Applied agreed to conform to the MESC communications standard — that is, the standard

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the 5000 is too restrictive to accommodate a wide variety of modules. Applied's own newer tools use a different size opening from that of the 5000. (John Dunn, private communication, June 8, 1992.)

[24] The move to 300 mm (12-inch) wafers is expected by the turn of the century, and will require a new generation of equipment.

that regularizes the hardware and software controlling the modules — but industry observers do not expect the company to adhere to MESC standards for their mechanical interfaces (Dorsch 1994). The most likely possibility is thus that competition will remain a matter of alternative technological trajectories, not of rival standards. To the extent, however, that new Applied machines are sufficiently open systems, it is possible that the company could offer their interface standards as an alternative, creating a genuine battle of the standards. A third, and perhaps least likely, possibility would be for Applied to offer a fully MESC-compatible machine. If the company takes the last route, it would find itself in a position similar to that of IBM in personal computers in 1981, that is, in a position to become the lead player in the provision of a single-standard modular system.[25] In a market in which external economies are significant, this can be a strategically desirable alternative (Langlois and Robertson 1992).

Implications for competitiveness.

In talking with industry sources and academic experts, one develops something like following the stylized picture of competition in semiconductors. The Japanese semiconductor industry is built around a commitment to manufacturing. This means mass production; a conservative philosophy that prefers incremental change and reliability to cutting-edge technology; and a large pool of production engineers at the fab level engaged in fine-tuning the production process. By having appropriated the market for DRAMs, the Japanese have taken the lead in the technology that drives advances in lithography and therefore in manufacturing technique. Apart from Nikon and Canon, which are themselves

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[25] IBM's situation was different only to the extent that, rather than adopting an existing public standard, it created a new bus and operating system. But the bus was in fact almost identical in concept to the S-100 bus already in use. Moreover, the MS-DOS operating system was virtually a clone of the then-dominant CP/M operating system, which would have had to have been updated anyway for the move from the eight-bit 8080 chip to the (quasi) 16-bit 8088 microprocessor (Langlois 1992).

large multidivisional firms with a core competence in optics, the Japanese equipment industry is largely controlled by the semiconductor firms themselves, either through vertical integration (in the case of Hitachi) or, more usually, through equity positions in what is described as a *keiretsu* structure. The manufacturers and their suppliers thus work in close coordination (Stowsky 1989).

By contrast, the American semiconductor industry has been better at product development than mass production, focusing more on logic and specialty chips and largely abandoning memories. This choice reflects in part the different structure of user demand in the United States, where computer and military applications dominated (Langlois and Steinmueller 1998). The Americans have focused less on manufacturing, and tend to rely more on their suppliers for process expertise. The fragmented equipment industry does not coordinate well with manufacturers, trusting to public information and market forces for its investment decisions.

The Japanese package worked well, at least until recently, and it has often been portrayed as a model for Americans to emulate. Although there is no doubt that American semiconductor makers must continue to increase their focus on manufacturing, it is not clear, however, that the Japanese approach has proven a durable and universally applicable model. For one thing, the strategic value of cutting-edge DRAM production is less obvious than it used to be. Most major companies now crank out some form of mass-produced chip as a technology driver, and the DRAM market has thus become a saturated low-profit one. The Japanese are beginning to feel the downside of the DRAM strategy, especially in view of the rise of Korean and Taiwanese production (Iritani 1996). Samsung is now the world's largest DRAM producer, and many in the industry feel that Korean firms, with newer and less-conservative process technology (much of it American), have gained cost leadership over Japanese firms. Moreover, Americans have improved their manufacturing capabilities, and the focus on product development may have had its positive side. Even if flexible production of specialty chips does not completely replace the mass production of generic chips, the days of the "capacity race" as the key element in semiconductor competition are probably numbered (Steinmueller 1992). And the Japanese have not proven able to crack American dominance in microprocessors, falsifying the predictions to the contrary that were widespread just a few years ago (Ferguson 1985; Reich and Mankin 1986). In addition to being a product with higher value added than DRAMs, microprocessors are also arguably process drivers: while DRAMs do drive lithography technology, microprocessors require more complicated intermetal connection, and tend to drive a number of critical mid-process technologies.[26]

What does this imply for competitiveness in the equipment industry? Much of the loss of American market share in that industry was the result of the movement of semiconductor production to Japan, where, with the notable exception of Applied Materials, American firms were not well able to compete. To the extent that manufacturing is recaptured in the United States and moves to other parts of the Far East (like Korea, Taiwan, or Singapore) where there is no indigenous equipment industry, the American industry may benefit.

Japanese manufacturing has been well served by a user-oriented equipment industry willing to tailor systems to precise needs. But one may wonder whether the closeness of that relationship, widely held to have been a great advantage so far, may not turn into something of a disadvantage in a world dominated by an open standard architecture. Japanese manufacturers themselves employ far more production engineers than in a typical American fab, shifting the locus of process knowledge away from the supplier and toward the manufacturer. This may not amount to a "deskilling" of the equipment makers. But there is a perception among Americans that their Japanese

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[26] An advanced 32-bit microprocessor would typically require four levels of metalization, whereas even the most advanced DRAM needs at most two.

counterparts are much more under the thumb of the manufacturers, who dictate profit margins and in some cases use the suppliers as little more than contract assemblers. American firms prefer the autonomy of selling “guaranteed” systems, that is, systems for which the supplier provides the bulk of technical knowledge and service. There is some move in this direction even in Japan, where service contracts (a substitute for close working relationships with suppliers) are on the rise (Dorsch 1991a).

Japanese equipment firms, including Hitachi, Anelva, Kokusai, Ulvac, Tokyo Electron, and ASM Japan, are developing cluster-tool systems of one sort or another, and the Japanese are closely monitoring the development of the MESC standards (Inaba 1989; Achiwa and Shankar 1990). It is certainly conceivable that Japanese equipment firms might become significant players in a future market for MESC-compatible systems. So far, however, the Japanese style has been distinctly proprietary,.[27] even if the recent turmoil in the Japanese capital markets may make some standardization more appealing in the future. In any event, however, the traditional relationship between manufacturer and supplier in Japan will not confer any special benefits on the Japanese equipment industry in world of standards, since a modular system is to a large extent a substitute for proprietary fine-tuning to user needs. Thus, if American firms can create reliable equipment, and especially if best of breed does become an important selling point, the innovativeness and product-development skills of the American industry may become a competitive advantage — if not in Japan then at least in the U.S. and in Asian markets outside Japan.

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[27] One exception is Sony, which acquired Materials Research, a leading American maker of MESC-compatible systems. Materials Research retains considerable autonomy, however, and continues to operate as an American firm. (Weinig 1990, Whiting 1991.)

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