The Modularity Trap:

Innovation, Technology Phase-Shifts, and Resulting Limits of Virtual Organizations[◆]

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Scholars have long noted that the technology of the firm shapes the organization of that firm (Burns and Stalker, 1961; Woodward, 1960). More recent scholarship has shown that the organization of the firm also conditions its ability to profit from its innovation activities (Teece, 1986). A number of scholars have examined the role of the type of technology in the ability of incumbent firms to adapt to innovation opportunities (Abernathy and Utterback, 1978; Tushman and Anderson, 1986; Anderson and Tushman, 1990; Henderson and Clark, 1990; Christensen, 1997). Some have argued that the organizational strategy of the firm must be aligned with the type of technology they choose to develop (Chesbrough and Teece, 1996; Tushman and O'Reilly, 1997).

This interaction between technology and organization is one useful way to approach the study of knowledge management. Because technology causes the environment to change so frequently, technology intensive settings provide researchers with abundant opportunities

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to observe the effects of change in a relatively short period of time. It provides, and indeed requires, explicitly dynamic approaches to managing knowledge, as Fiona Murray (among others) has argued elsewhere in this volume.

This paper builds on this prior research by developing a contingency framework for firms to align their organizational strategy with the technology that they are pursuing. It advances the idea that the character of technology is not static; rather, it evolves from one type which we will term integral (to be defined below) to an opposite type we will modular (also to be defined below), and then cycles back. As the technology shifts from one phase to the other, the optimal organizational configuration of the firm must also shift, if the firm is to continue to capture value from its innovation activities.

However, the optimal alignment to a technology phase-shift can be quite difficult, and many firms often fall into organizational misalignment. In this paper, we develop a conceptual framework of such organizational traps that helps to understand how and why a firm fails to capture value from innovation when facing technology phase-shifts. We apply the framework to the hard disk drive industry to illustrate the explanatory force of our framework.

Our major concern is with what we call a “modularity trap”, in which a firm that has successfully aligned its organization with a modular phase of technology, encounters great difficulty in capturing value from its innovation activities when the technology phase shifts from modular to integral. As discussed below, in a modular phase, firms that follow virtual organizational strategies match their internal organization to the modular technological characteristics of that phase. They coordinate much of their innovation activities through the

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helpful comments on earlier drafts. Chesbrough wishes to acknowledge financial support marketplace, where independent firms come together to buy and sell technologies and the components that embody them (Chesbrough and Teece, 1996). Since this strategy can maximize flexibility and responsiveness in a changing marketplace, the virtual organization appears to provide a powerful and predominant model in many industries as PCs, biotechnology, semiconductors and so forth. In these industries, many large, integrated firms have been outperformed by smaller, more focused competitiors.

However, we do not think that modularity is the inevitable end-state of technology. Rather, we see technology developing in cycles, where new discoveries shift the character of technology towards a more integral phase. This shift can create a serious problem for highly focused firms that we term a "modularity trap". Virtual organizations have succeeded by focusing their energies on a specific area of technology, but lack the systems expertise that can respond to new technologies that rearrange the boundaries of technology. Their singleminded focus within a specific configuration of technology now becomes a significant liability. We will motivate our reasoning for these technology shifts, and the resulting organizational responses below, and then illustrate their impact through recent research we have conducted in the Japanese hard disk drive industry.

Technology-Phase Shifts and the Need for Organizational Alignment

When a totally new technology emerges, technology development in the industry is usually in a phase we term integral (following Christensen and Chesbrough, 1999).[1] Here, the technical information of how the different elements in a system function together is not well defined, and interactions between elements are poorly understood. The new technology

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may offer a tremendous improvement in performance or cost, but many other elements required to transform a promising idea into a commercial product have to adapt, in order for this potential to be realized. This is the opposite of truly modular technology (Henderson and Clark, 1990), whereby new components simply plug into the existing architectures without a hitch.

Because these integral technologies are only poorly understood, their numerous interactions cannot be fully characterized. This complicates the problem solving that must be done to develop the technology further. Under these conditions, intermediate markets do not function effectively and can even be hazardous. A customer cannot fully specify his requirements to a buyer. The buyer can develop a product that meets the literal specification, only to find that the customer returns it because it doesn't work in the customer's product. When these problems arise, independent companies may reasonably differ as to their cause. Each may want the other to do more (and bear more of the costs) to resolve the situation. Customers and suppliers may also wish to avoid highly specific solutions to a particular problem, for fear of being locked into each other and being exploited later on. Because the interdependencies are poorly understood, bringing in another supplier is a costly alternative that may not even solve the problem. Worse, a new supplier may introduce new technical problems which again may be viewed differently by the different parties to the transaction.

To achieve the close coordination and to facilitate rapid mutual adjustment between interdependent technologies, administrative coordination outside of the market is required to develop the technology effectively. An internal or captive supplier of an interdependent component technologies has three general advantages in managing this complex internal coordination, relative to firms who coordinate through the market. One advantage is in superior access to information. The second is weaker incentives to exploit temporary advantages inside the firm, and the third advantage is tighter appropriability of the returns generated by the solutions to technical problems. We will consider each of these in turn.

The information advantage is that there is less “impacted information” (Williamson, 1975), so more information can be shared more quickly within the firm than can be shared across firms. Firms have the ability to access even very detailed findings within their walls, such as the results of specific tests and procedures, and all information created within the firm is the property of that firm. Employees have no legal right to withhold such information. Moreover, employees usually expect to stay at the firm over time, giving them an interest in cooperating today in return for receiving cooperation tomorrow on another project. Arms-length coordination through the market contains none of these features. One firm has no legal right to the results of tests conducted at another firm, and firms strategically can choose what information to share and what information to withhold. Moreover, the very fact of dealing at arms-length means that neither party can be assured of working together in the future. Each firm may manuever to encourage other suppliers or other customers to create greater freedom of action, in part through strategically sharing and withholding information. This reduces the “shadow of the future” around their current dealings.

The incentive advantage is one of “low powered incentives” (Williamson, 1985). Individuals within different divisions that must coordinate have relatively little to gain directly from exploiting a temporary advantage over individuals in a sister division. Their division’s stock is not directly traded, and the gains of one division and the losses of the other are pooled together in the firm’s overall stock price. Relative to firms transacting through the market, neither division has much incentive to withhold cooperation with the other, or to renegotiate for better terms with the other party, as part of resolving the technical issues. The bargaining costs for coordinating technical problems become attenuated, relative to what they would be for independent companies.

The final advantage is that of tigher appropriability (Teece, 1986). Divisions within a firm that attempt to resolve complex technical interdependencies have a higher assurance that they will capture part of the gains from resolving those problems. The likelihood that either division will hold up the other is attenuated by the information and incentive advantages within firms noted above. As a result, technical problem solving can be undertaken with the confidence that the resulting solutions will not be used to undermine the position of one of the coordinating divisions in a later stage renegotiation.

For these reasons, firms that follow integrated organizational strategies will match their internal organization better to these integral technological characteristics. Integrated configuration of innovation activities allows firms to manage the interaction effects between technical elements, and to share information freely without worrying about distortions in subsequent bargaining over the terms of exchange between the units.

However, technology may shift into a phase we call modular. In the modular phase of technology development, de facto and de jure standards develop that articulate and codify the interactions between elements of a system. These are often termed “dominant designs” (Tushman and Anderson, 1986; Anderson and Tushman, 1990). These standards permit even complex components to be substituted for one another in a system. The presence of these standards and associated know-how creates enough codified information to enable markets to coordinate the integration of technology across the interfaces between stages of value added. Rival suppliers with interchangeable products discipline one another to promote strong competition within these standards, resulting in more rapid advances in technology and lower prices to systems customers of those component products.

In these circumstances, virtual firms are indeed “virtuous” (Chesbrough and Teece, 1996), compared to firms that continue to manage these coordination activities inside the firm. The earlier information advantages within the firm have been rendered insignificant by the advent of techncial standards. These standards codify the technological interactions sufficiently that relatively little technical ambiguity remains to be clarified. The establishment of standards permit numerous firms to experiment with a variety of implementations, and the resulting diversity far exceeds what experiments a single firm could conduct inside its walls. The very basis of competition shifts from constructing complex systems with integral designs to more horizontal competition within individual layers of technology, bounded by these standards.

The incentive characteristics within firms remain low-powered, but this now becomes an impediment, instead of a virtue. The presence of established standards permits multiple firms to compete at each level of technology. This competition disciplines each competing firm, stimulating greater risk taking, and providing a credible alternative source of technology should any firm attempt to hold up another. Since markets can now function effectively to coordinate technical development within these standards, high powered incentives lead to more advanced technology sooner. The presence of alternate credible sources similarly resolves potential appropriability problems, because suppliers have alternate customers, and customers have alternate suppliers. Each can only expect to profit from their value added within their level of the technology.

Firms that follow virtual organizational strategies effectively match their internal organization to these modular technological characteristics. For virtual firms, focusing within a single layer of technology harnesses the strong incentives and high volumes available through the market. The ability of standards to coordinate their actions within a larger systems architecture mitigates coordination hazards, and enables these firms to move fast.

These focused firms force larger firms with divisions in multiple layers of a technology to adopt more decentralized strategies themselves, in order to remain competitive in this phase of technology. This decentralized organizational strategy must enable units within the firm to buy and sell components independently in these modular technology markets. In particular, decentralized organizations eschew corporate dictates to use captive sources when market conditions make this choice unwise, and similarly avoid corporate commands to refrain from selling technology to outside rival firms.

The overall model, therefore, is one in which phase-shifts in the character of technology require organizational reconfiguration in order to effectively develop that technology. An important implication of the model is that the organizational strategies that integrated firms need to employ to appropriate the value of the technologies they develop through research must change in response to increasing or decreasing degrees of modularity at these interfaces. Because technological change and scientific discovery can alter the phase state of technology in an industry, firms must be prepared to adjust their organizational approach in order to profit from their technology.

To profit from innovation, therefore, firms must assess the condition of the technology upon which their business is based, and then adopt appropriate organizational policies and structures based on that assessment. Firms which align their structures well will profit from their innovation activities, while firms that do not so align themselves will fall into organizational traps that we will describe below. These traps will frustrate their ability to capture value from their innovation investments.

The linkage between organizational alignment and technological phase state can be depicted in a matrix, shown below in Figure 1.

[Figure 1 about here]

Figure 1 displays the interaction between organization and technology, and where value can be captured or dissipated. The upper left quadrant reflects the appropriate alignment of a decentralized or virtual organizational strategy with a modular technological phase. Here, value is realized within each technology module, and the external market manages the linkages between the modules, avoiding inefficient internal interactions. The lower right quadrant depicts the appropriate alignment of a centralized organizational approach with an integral technological phase. Here, value is realized through the ability of internal coordination mechanisms to manage the complex interactions of the technology. This value arises in large part because the market cannot manage these interactions itself. Here is where the information and low powered incentive advantages within firms pay off.

The “off diagonal” quadrants indicate cases of misalignment, or organizational traps, where value can be dissipated, due to an inappropriate organizational approach towards the technology. These are the focus of the rest of the paper, so we will describe them in some detail, and illustrate them with recent research findings in the Japanese hard disk drive industry.

The Shift to a Modular Phase and the Integrality Trap

The history of many technologies reveals that the character of technology can cycle from very integral states to very modular states, and back, as shown in Figure 2.[2] In the early stage of a industry, technology underlying the product system is usually quite integral, implicitly encompassing substantial interdependencies between elements. At this time, how different technological elements interact each other remains unclear. In the integral phase of technology, firms must learn and accumulate integral knowledge concerning interdependencies and interactions between technological elements at the whole product system level. However, integral knowledge is by definition context-specific and difficult to articulate in documents. Thus, it is rather tacit, and usually embedded in one's experience as know-how (Nonaka and Takeuchi, 1995).

[Figure 2 about here]

In this phase of technology, integral knowledge is a driver for an outstanding product, which sometimes results in radical or architectural innovation (Henderson and Clark, 1990). Integral innovation improves functionality, quality and cost of the product system, based on a new integral knowledge that describes how to coordinate interdependent technological elements and components within that system more effectively and efficiently. Given the tacit, context-dependent nature of integrative knowledge, however, realizing integral innovation requires a series of experiments, trials and errors, and continuous learning-by doing, which consequently takes a long time. Through these experiences, firms gradually come to understand how the different technological elements and components constructing the product system interact with each other. They may develop tools, specialized equipment, testing procedures, and simulations to understand better these complexities. As a result, technological interdependencies between elements lessen, and interfaces between components become gradually clarified.

Hence, a technological shift to a modular phase is based on continuous, incremental accumulation of integral knowledge. The increasing understanding of technical interdependencies, and the associated creation of tools, models, simulations and equipment to manage them, all culminate in a shift of the technology towards a modular phase.

This dynamism can lead to misalignment of the organization and the technologies it is developing. When technology moves from an integral state to a modular state as technological interdependencies become well-known, a firm that participates in both upstream materials and downstream components (or upstream components and downstream systems) can only capture the value they add at each stage of the value chain. The shift to a modular phase effectively dissipates the earlier value obtained from coordinating these different stages of technology together inside the firm.

If firms prove unable to adapt their organizational configuration to the dictates of the phase of their technology, organization traps will result. If they remain integrated when a technology becomes more modular, an “integrality trap” arises, in which the firm relies on administrative mechanisms to accomplish technical coordination that other firms are able to accomplish through the market. This is depicted as the lower left hand corner of the matrix in figure 1. The misalignment causes firms to continue to pursue internal coordination activities when these activities are now well managed through the technical interfaces and standards in the market.

Why are firms often caught in the integrality trap? The mechanism underlying the integrality trap is closely related to the paradox that integral innovation triggers the shift to modular phase of technology. As mentioned above, whether the innovation is based on changes within each component (modular innovation), or on new ways to coordinate and combine technological elements (integral innovation) provides a critical dimension to classify innovations. It is rather misleading to understand the type of a particular innovation by only looking at its ex post configuration along the modular-integral dimension. Each innovation is by nature a dynamic process: a firm first perceives the source of innovation and its potential opportunity for a better product, and then exploits the source to realize an innovation with a paricular configuration. This is shown in Figure 3.

[Figure 3 about here]

Thus, an innovation can be viewed from two different angles, as shown in Figure 3. The horizontal dimension captures the ex post configuration of a innovation realized. As we have discussed, this dimension determines effective organizational alignments to exploit the value from innovation. On the other hand, the vertical dimension captures the source of the innovation: whether it is comprised of particular elements, or by the combination of those elements. Framing in this way, an innovation can be characterized by interaction between source (ex ante expectation) and configuration (ex post exploitation) of the innovation. Viewing an innovation as the interaction is important, because an innovation that has its source in a progress of integral knowledge does not necessarily result in an integral innovation, nor does an innovation first realized in a specific component always result in a modular innovation. To the contrary, modular innovation often has its root in integral innovation (improved understandings of combinations of technological elements, and conversely, integral innovation is often triggered by modular innovation (a change in a particular element or component). The important point is that such "gaps" between a source and a configuration of innovation are typically observed when technology shifts from integral to modular, or conversely.

In a phase where technology is stably integral (Phase I in Table 2), a firm will find a source of innovation as integral (a possible better way to combine elements), and then it may expoit the opportunity for developing a better product through integral innovation. In this phase, therefore, an innovation is "simply integral," and there is no gap between the ex ante source and the ex post configuration of the innovation (the upper-right cell of Figure 3). As firms deepen knowledge about interdependencies of elements and components through integral innovations, technology will be in a transition phase (Phase T-a), gradually shifting toward modular. In this state (the upper-left cell), some firms may exploit the opportunity derived out of preceeding integral innovations so as to to realize modular innovation, but at this time of phase transition, it is often difficult because modular innovation requires a firm to first freeze interfaces between technological elements in order to handle each element in an isolated fashion. Firms that have held leadership in the integral phase possess much integral knowledge to make the product still better. Approaching modular innovation appears perverse (at least to such firms), because this forces them to stop improving their integral knowledge, and even to throw away their integral-knowledge-based advantages. If they try to develop better products, it will appear much more effective and efficient for firms with rich integral knowledge to continue to pursue integral innovation. This "rational" approach will avert them from aligning their innovation activities to modular innovation. This provides a basis of organizational inertia that results in the integrity trap.

When Technology Shifts to an Integral Phase: the Modularity Trap

The organizational misalignment can work in the other direction as well. Firms that have effectively pursued virtual approaches when their technology was in a modular phase can get into trouble when the technology shifts to an integral phase, if they don't also shift their organizational configuration to a more centralized one. If a firm remains virtual as its technology shifts to a integral phase, a "modularity trap" ensues, in which the firm lacks the systems knowledge and experience to comprehend the new interdependencies involved in the technology. The firm is no longer able to specify its needs and requirements adequately to its outside suppliers, so its now-familiar problem-solving routines no longer prove to be effective. The supply chain linking the horizontal technology layers is unable to achieve the requisite coordination to develop the technology, relative to internally-organized firms.

The logic underlying this modularity trap comes from another paradaox: the technological shift to integral phase can be often triggered by modular innovation. Going back to Figure 2, after the phase transition from integral to modular (Phase T-a), technology goes into stably modular phase (Phase M). In this stage, innovation bocomes simply modular. Firms try to exploit the innovation source at the component level to realize modular innovation in order to develop a better product, as shown in the lower-left cell of Figure 3. However, modular innovation can sometimes be a source of opening up needs to deconstruct established ways to combine technological elements and components, and consequently forces firms to learn new integral knowledge about how to manage the interdependencies of different elements for developing a better product by using the modular innovation. Such disruptive modular innovation can result in a technology-phase shift back to integral, where how different technological elements interact each other becomes unclear again (Phase T-b in figure 2). At this time, the ex post configuration of innovation should be integral, while the source of innovation itself is still modular, as shown in the lower-right cell of Figure 3. This distortion in the process of innovation can invite firms into the modularity trap, which is depicted as the upper right hand quadrant of the matrix in Figure 1.

Firms that have enjoyed advantages of virtual organization in the modular phase of technology will encounter great difficulties in this situation. These firms may find that it is quite difficult to exploit value from the modular innovation, because it will not contribute to developing a better product without substantial coordination and interaction between technological elements. Such ex post problems will seriously handicap them to capture value from the innovation, because firms following a virtual organization strategy lack experience and understanding at a systems level that is now necessary for coordinating integral knowledge.

This modularity trap is a real trap to firms with virtual organization strategies for the following two reasons. First, it appears very rational and even easy for such firms to react to the modular innovation opportunity by making the best of current virtual organization. Because the innovation source itself lies in a specific technological element or component, its opportunity appears very clear to them. Furthermore, firms following a virtual organization approach may quickly and easily access components that embody the modular innovation, because, after the preceeding modular phase, there are usually several independent firms that specialize in making and selling the component in the marketplace. Hence, for virtual firms, the modular innovation appears as more of an opportunity than a threat in terms of their ex ante expectation. Given the mechanism of the phase shift back to integral, virtual firms will remain virtual in order to make the best of their advantages in responsiveness intensively and extensively, simply because this is a quite “rational” way to react the innovation that have its root in a change at the component level. They will find themselves caught in the trap only after encountering ex post problems of interdependencies and interaction between components.

Second, and very importantly, a technology shift back to integral phase usually occures in a much shorter time span than a shift to modular phase, while modularization takes relatively long time due to the incremental nature of progress in integral knowledge. A shift back to integral phase is triggered by a change in modular knowledge which is more explicit and context-independent. Once a firm introduce a modular innovation that consequently requires major changes in how elements and components interact each other, the stable interfaces between elements are broken immediately, and technology moves back toward an integral phase.

This rapid shift makes it even easier for firms to fall into the modularity trap, and makes it more difficult for firms to escape from it. Firms cannot afford to gradually adapt themselves to the new phase, given its immediacy. Even if they try to develop integral knowledge by themselves for solving the coordination problems, this choice may result in a serious competitive penalty because creating integral knowledge will take a long time. Alternatively, they may rely on problem-solving effort by independent suppliers. But the earlier hazards of specificity and of bragaining costs between the parties arise again, making coordination problems still more difficult. Thus, virtual firms are subject not only to the modularity trap, but face a difficult dilemma in escaping from the trap.

Technology Shifts and Organizational Misalignment in the Japanese HDD Industry - Thin Film Heads

We examine these issues now through field research we haved jointly conducted in the Japanese hard disk drive market. The hard disk drive industry is one that has experienced technology-phase shifts, and we believe this has resulted in organization traps for some firms in that market.

Hard disk drives consist of many different technological components, including read-write heads mounted at the end of an arm that flies over the surface of a rotating disk; aluminium or glass disks coated with magnetic material (often called “media”); electric motors including a spin motor that drives the rotation of the disks and an actuator motor that moves the head to the desired position over the disk; and a variety of electronic circuits controlling the drive’s operation and its interface with the computer. While each of these component elements has evolved rapidly in the past few decades, we will focus primarily on the evolution of disk drive head technology.[3]

Through the 1960s and 1970s, the hard disk drive industry employed iron or ferrite heads that were mechanically ground to the correct tolerances for integration with iron-oxide media into a hard disk drive. This technology was in a rather modular state, as the mechanical and electrical properties of ferrite heads were becoming well understood, enabling many companies to use outside suppliers, and enabling suppliers to enter the market and offer their heads to drive manufacturers.

There was a problem however. The known characteristics of ferrite heads indicated that a limit would eventually be reached that would require a new type of head to be developed, if the industry were to continue to advance its technology beyond that limit. In anticipation of this eventual limit, IBM began development of prototype thin film heads at their Yorktown research labs in the mid-1960s, and IBM announced proof of feasibility for use of this new material in magnetic recording in 1971. This announcement triggered the initiation of research and development activity in other firms in that year.

However, solving this problem caused new problems to arise. It turned out that utilizing thin film material in a disk drive head required numerous extensive changes in other parts of the disk drive. The design of the head depended both upon the design of other components in the system, and upon the architecture of the system itself. And the designs of these other elements of the product in turn were predicated on the design of the head. The head-disk interface, for example, was far different than it had been under the earlier ferrite technology. The new head required differences in the disk media, in order to reliably read and write data with the new material. There also were changes in the methods of error correction that had to be developed to enable the new material to record reliably.

In order to sort out the many technological interdependencies in the initial development of drives with thin film heads, product development teams had to do their work in a tightly integrated, iterative manner. The earlier, well understood design rules that developed around ferrite head technology no longer applied, as use of the old rules generated error conditions that had not occurred before. The new rules that would allow thin film heads to be used in a disk drive design had to be discovered via trial and error. Depending on the problem, the solution might be implemented in the head design, in the design of the head stack, in the media coating or surface, in the read channel electronics, or in the low level software (called firmware) that controlled the disk drive functions.

The independent head companies such as AMC struggled mightily in the face of this technology shift. While they proved able to make a number of incremental improvements to ferrite head technology that extended the life of that technology well beyond the original anticipated limits, they were at a severe disadvantage in attempting to develop and market the new generation thin film head components to drive manufacturers. Their customers could not fully specify the attributes they needed from AMC in their heads, nor could AMC anticipate their needs entirely. Samples of heads from AMC did not work in the new designs, and determining how and where in the design and components to correct errors was an intricate process. Moreover, when AMC corrected early problems with revisions to its head designs, these triggered new problems in the head-disk interface, the disk surface, and the associated electronics.

We view this situation as an example of a "modularity trap" that engulfed AMC and its drive customers. Independent head companies in this era knew well how to engineer well-characterized technology like ferrite heads, and were effective in competing with that technology. When that technology matured, and was starting to become obsolete, however, these same firms didn't have the systems knowledge and perspective to create new technology with new materials, and resolve the myriad integration issues with the other elements of the disk drive.

In comparison to AMC, IBM clearly benefitted from its organizational strategy at this time in the industry. Because of its integrated organization with awesome capabilities in research and development, it was able to establish a lead of many years in the deployment of thin film heads in hard disk drives. IBM also followed a policy of not selling its heads, or its disk drives, to other disk drive and systems companies respectively. This policy was also effective, as the integral nature of thin film heads at this time precluded the creation of an active merchant market for them for many years' time.

The Phase Shift in Thin Film Head Technology Towards Modularity

Eventually, the mysterious attributes of thin film heads were sorted out by hard disk drive makers and independent component manufacturers (many of whom hired a number of key engineers from IBM, and who then diffused important know-how from IBM to the independent manufacturers). As the technology became well understood, the independent firms could tool up their production lines to serve demand from any and all of their customers, giving them the potential to serve the entire market. They learned to work with suppliers of media (the disks in the disk drive) to develop new generation heads. Characterizations of the interactions became stabilized, test equipment companies developed tools to verify these characterizations, and suppliers could be coordinated through conformance to these characterizations. Alongside AMC came new entrants like Read-Rite, whose sales of heads mirrored the maturation of the thin film technology – rising from $28 million in 1988 to $345 million in 1992.

The development of independent firms making high quality heads in very high volume, along with the parallel development of other companies in the US and Japan mastering the thin film technology, meant that IBM no longer enjoyed a proprietary technological edge due to its capabilities in the technology phase shift from modular to integral. As knowledge of that technology diffused widely throughout the industry, its character gradually changed from an integral technology to a highly modular one.

IBM's organizational strategy, however, remained inert to this phase shift in technology. It continued to restrict consumption of its heads to its own disk drive division, and similarly limited the sale of its drives to its internal systems divisions. By eschewing outside sales of its now-modular technology, IBM fell into a different organizational trap, the integrality trap. Thin film heads have high fixed development costs, and require high volumes to amortize these costs. IBM's posture limited its total volumes of heads to its internal needs. IBM's internal volumes suffered as a result of other problems in its drive business at this time that have been documented elsewhere (Christensen, 1992a; 1992b; 1993), resulting in rather low volumes. As a result, IBM was a high cost producer of a technology it had invented.

This policy imposed a double penalty on IBM's drive business. It was not able to source heads on the merchant market, and instead was mandated to use its own heads. Because of their lower volumes, these heads were more expensive than those used by IBM's drive competitors – imposing a significant cost penalty upon IBM's drives. This penalty was compounded by a second effect. Because IBM could not sell its heads to other companies, it could not garner the volumes from those companies to reduce its costs further. As other companies volumes and market share grew, IBM's cost disadvantage grew accordingly.

The Emergence of MR Heads: an Integral Technology Phase Shift

The continued rapid pace of technical advance in the hard disk industry meant that thin film technology itself was going to encounter limits as well. IBM's research labs were developing a new type of head technology, called "magneto-resistive" (or MR) heads. MR technology represented another tremendous advance beyond thin film heads that promised to increase the potential recording density of disk drives by ten-fold, but again its initial character was extremely opaque. The IBM announcement of the development of the technology quoted the lead engineering manager on the project who said "We don't fully understand the physics behind the technology, but we are able to replicate it fairly consistently." (SF Chronicle, August 15, 1992, p. D1)

As in the earlier case of the initial thin firm heads, the established design rules and models had to be thrown out. Once again, new problems emerged that hadn't been experienced before in designing disk drives. Two particular problems that were commonly encountered were electrostatic discharge (ESD) and thermal asperities (TAs) that illustrate the interdependencies of deploying integral technology.

ESD was commonly encountered in the disk drive manufacturing process, and every company had learned to take steps to protect the drive heads and drive electronics from it. What was new was the extraordinary sensitivity of MR heads to even trace exposures to ESD. An MR head could be processed through to completion, tested, and then integrated into a hard disk drive, but then fail to function in final test – though these processes had previously proved more than sufficient to manage ESD problems in thin film head designs.[4] A number of approaches were tried to resolve the problem, in the design of the head itself, in the packaging for the head, in the disk drive design, and in the manufacturing process. One firm reportedly spent over $10 million just to rip up the floor tiles of its manufacturing facility to install special flooring that inhibited even minute transmissions of ESD.

TAs are physical defects that the MR head creates in the spinning disk. This is a new problem, resulting from the confluence of ever lower flying heights for the heads, higher temperatures for the writing of data by the MR head than earlier heads, and texturing of the spinning disk surface. A TA is created when the flying head inadvertantly touches the disk during operation. The resulting contact generates heat, which caused the particles at that portion of the disk to swell, and distorts the signal recorded at that spot on the disk. Normal error correction codes often cannot rectify these errors, because the length of the defect can exceed the length of the correction code.

Both the ESD and the TA phenomena were symptoms of a more general condition: the disk drive head technology had shifted back to an integral phase state. Once again, independent head manufacturers and their disk drive customers ran into tremendous difficulty adapting to this new technology. Non-integrated US companies such as Western Digital, and Maxtor, who had prospered during the modular state of thin film head technology, struggled mightily with independent head suppliers such as Read-Rite, to adjust to the demands of MR head technology.

Each firm reported significant negative earnings impacts from trying to adjust to the new MR technology during this period. Western Digital lost over half of its market capitalization in 1997, and analysts attributed this loss to its inability to successfully incorporate MR head technology into its next generation disk drives. Maxtor was forced to sell itself to Hyundai, to obtain sufficient capital to remain in business. Quantum recently discontinued its captive MR heads activities that it had acquired from Digital in 1994. This was the largest factor in a charge to Quantum's earnings of $190 million (Wall Streeet Journal, Feb. 23, 1999: C1).

Japanese Firms' Responses to MR Technology Phase Shift

Nor are US firms the only firms to have fallen into this trap. We explored the response of the four leading Japanese hard disk drive firms (Fujitsu, Hitachi, NEC, and Toshiba) to these technology phase shifts. We learned that NEC, after more than twenty years of designing disk drives, has decided to discontinue current generations of drive design work in MR, and has chosen instead to partner with IBM to manufacture IBM designs in NEC's factories for NEC’s systems businesses. These designs will incorporate IBM’s MR components into IBM designs, and allow NEC to produce competitive disk drives, albeit not of their own design. We think this decision reflects NEC’s virtual approach to MR technology, and its resulting inability to master MR’s newly integral character.

Another Japanese drive manufacturer, Toshiba, appears to have fallen into the trap as well. Unlike NEC, Toshiba continues to develop its own disk drive designs, but relies on outside suppliers for its heads and media. Toshiba had focused its skills on rapid time to market for modular technologies for its 2.5” hard disk drives, many of which were employed in its own notebook systems. Toshiba initially treated the advent of MR heads as a rather minor extension of earlier head technology. When Toshiba developed its first MR drive, there were no off-the-job/on-the-job training programs for engineers to master MR technology. In fact, the first MR drive development program did not even have a unique project code name. For Toshiba, its first MR drive was just another product development following its earlier hard disk drives with thin film heads. Considering that the hard disk drive technology had been in a modular phase until the MR head innovation, Toshiba’s virtual organizational strategy appeared effective. One manager mentioned the importance of component outsourcing in the HDD business:

> “It was very crucial for us to have good outside suppliers of key components in order to achieve efficient product development. In-house development of key components requires heavy investments, taking effort over a long time. We have tried to have at least two suppliers for a particular key component like heads, because such approach contributes to stable supply and cost reduction of components through competiton

> between outside suppliers, as well as avoiding risks of investment into component development."

However, Toshiba's virtual approach consequently faced difficulties in developing its MR drives. One manager described the resulting problems they encountered during the development of Toshiba's first MR drive:

> "We viewed HDD competition as purely a matter of speed. The advantage for first movers is great. If you are three months late, your profit will be only 30% of the first mover's. But, in the case of MR heads, Toshiba could not be first. We tried to define the specs we required for our heads. But we couldn't completely specify them, because we were less knowledgable about MR heads than our suppliers. When we faced technological problems unique to MR drives, we thought that it was even wiser for us to rely on our suppliers' problem-solving efforts. For example, the process of manufacturing MR heads was so complicated that it was difficult for us to specify how to do for improving the performance of MR heads. It appeared more effective and efficient for us to leave the major part of head-related problem-solving in suppliers' hands simply because they were component specialists and knew more than us. "

Though Toshiba's development engineers frequently communicated with suppliers through drawings and specifications, thay did not have a working-level collaboration. When they faced problems, they relied heavily on problem-solving efforts from each supplier. For example, when Toshiba encountered the TA problem, the problem-solving effort by Toshiba itself was limited to controlling the level of particles in the drive assembly process. They left most of the TA-related problem-solving to outside suppliers of heads and media, simply setting a target of functionality and proposing that suppliers intensify their testing of component quality. This hands-off approach of Toshiba consequently narrowed possible paths to the problem-solving. For example, the correction of TA only on the head side inevitably took a very long time (between three to four months) because the manufacturing process of MR heads requires many complicated steps, like a semiconductor fabrication process.

Toshiba's difficulties with using MR heads in its hard disk drives has caused them to change their head suppliers. To date, it has tried three different head vendors. Recently, Toshiba started to use MR heads from Headway, a US head supplier, because Headway's MR heads were originally designed to prevent TAs, incorporating an auto-cancelling mechanism based on technology developed by Hewlett-Packard. Using Headway's heads in disk drives required a different pre-amplifier, but it is a standard component that can be easily purchased in the marketplace.

Although Toshiba has thus tried to solve the MR-head-related problems through a way that fits its virtual organizational strategy, they are still having many difficulties working with them to resolve technical issues in utilizing MR technology. They did not ship MR drives until four years after IBM, and their market share in 2.5" drives has fallen by 10 percentage points, while IBM has increased its market share in 2.5" drives by a corresponding amount (IDC, 1998).

Not every Japanese disk drive firm fell into the modularity trap. For example, Fujitsu was able to master the MR technology more effectively. This was due to its continued investments in systems knowledge and materials and component technology in its R&D labs. At the time of introducing its first MR drives, there were four different labs engaged in the

MR drive development. Fujitsu Laboratory, a corporate lab, conducted long-term, MR-head-related material research. In December of 1993, 35 engineers were transferred from Fujitsu Lab to a division lab (Storage Technology Lab), including 10 engineers who focused on head technology. At that time, however, only five engineers had specialized in MR technology, because using MR heads had been only an option among three different technical approaches. In 1992, Fujitsu Lab also pursued thin film heads and vertical heads as well as MR heads for future possible technologies. Starting with the five engineers with MR-related expertise, Fijitsu had gradually mastered MR technology in a learning-by-doing fashion. One engineer described Fujitsu's approach in the early stage of the MR head development:

> "At that time, we had neither an off-the-job nor on-the-job training program for mastering MR technology. This was simply because most of us did not fully understand what the MR was. What we did was 'on-the-job learning' which included lots of trial and error. However, our in-house approach had some good things. Though we had not been so knowledgeable about MR, we could be rather careful about how to deal with the new technology when using it within the HDD product system as a whole. From the beginning, we were alert to potential interface problems between new MR heads and media."

On the division side (Storage Products Group), three development units conducted MR drive development from different perspectives. The Storage Technology Lab focused on future technologies for key components including heads, media, LSIs and mechanism design as well as the HDI (Head-Drive Interface). The Storage Component Division developed components for the next generation HDDs. Not only did they develop key components, they also built the high-end, state-of-the-are HDDs that used these components, developing systems knowledge with these new components. The HDD Division was responsible for developing current generation HDDs with project teams, each of which was organized for a particular model. HDDs for desk top PCs and mobile PCs were manufactured in this division.

Fujitsu's integrated organizational startegy gave it mastery over the many interdependent elements in the new MR-head disk drive. It's approach to solve the noise problem provides a good example. Controlling noise level was a technically subtle problem because it was embedded in a complicated manufacturing process unique to MR heads. They first tried to control the noise by improving the manufacturing process, but this effort could not reach the expected level of the noise control. Hence they went back over to material development, which needed research-oriented technology developed at the Fujitsu Lab. The development engineers had intensive collaboration with the Storage Technology Lab, and decided to bring forward the use of advanced materials that had been under development at a research group in the lab for a future generation. This finally contributed to overcoming the noise problem of MR heads. Fixing errors due to TAs as well as the problem of a gap between the read- and write-parts of a head also required engineers to carefully understand the complicated interdependencies between heads and other parts of a HDD. Most of these technical problems were found only after assembling components into a prototype. Head engineers had intensive communication and collaboration with those on the drive side (the mechanism, the LSI electronics) in order to resolve the interdependencies. Though the problem appeared on the head side, efforts on the drive side like error-correction LSIs and controlling mechanisms turned out to improve the quality and functionality of MR drives most effectively. One manager described how the integral knowledge was applied to the resolution of TAs induced by the shift to MR heads:

> "We saw two avenues to correct this problem, the drive side or the head itself. Seemingly, the problem was head related. However, taking this head approach often resulted in costly and time consuming approaches. Correction efforts on the drive system side substantially contributed to solving the problem. It was faster to think of how to recover from the asperity in the drive system rather than thinking of how not to make the noise. This problem solving required the coordinated efforts of many departments, such as the Fujitsu Central Lab, the Storage Technology Lab, the Storage Component Division, and the Hard Disk Drive Development Division. We were sceptical of relying on only the head suppliers to fix this problem, because they may define the problem too narrowly, and this may limit their ability to find the most effective solution to the problem."

Fujitsu was able to leverage its capabilities in these different areas quite directly by co-locating these functions for extended periods of time until interdependencies were resolved. For this cross-functional integration, working group meetings held in the Storage Component Division located in Nagano played an important role. Engineers in the Storage Technology Lab (located in Astugi and Kawasaki) and those in the HDD Division (located at Yamagata) got together in the working group organized in the Storage Component Division. For a working group meeting, engineers from Atsugi, Kawasaki and Yamagata usually stayed in Nagano for one week in order to resolve the problems due to interdependencies. Such working group meetings were held at least twice a month during the MR drive development. The Storage Component Division was a good place for the working group meetings, because it had manufacturing facilities while there was only a small-scale pilot plant in the Storage Technology Lab. It was important for the working group to verify the effectiveness of their development by actually manufacturing the HDD prototypes, using the facilities in Nagano. :

> "Facing MR technical problems, it was critical to consider how best to recover. Should we change the head, its packaging, the mechanical assembly, or the electronics? This was difficult to answer, because the MR technology was so unclear at this time. We needed to make lots of experiments and prototypes, to use trial-and-error to explore alternate solutions. Due to the strong interdependencies of the head-media interface, our head guys and media guys usually worked together in the same room for solving these problems."

Hitachi also possessed similar capabilities, due to its own corporate labs such as the Central Research Lab, the Basic Research Lab, as well as its product development divisions' labs and advanced development groups. In 1991, the Advanced Technology Development Center was established in the Storage Systems Division, and 100 HDD-related engineers were transferred from a variety of corporate labs to the Center for MR drive development. These different groups brought different strengths and perspectives to the challenges of MR. Hitachi made extensive use of co-location and cross-functional problem solving to address problems posed by MR technology. In order to resolve the ESD, some engineers in the head design group went to Hitachi's Musashi Works of the Semiconductor Division to learn how to improve the manufacturing process of MR heads, which resulted in considerable improvement in terms of their yields. As for the TA problem, Hitachi pursued two ways of problem-solving. First, given the experiment data from the HDI group in the Storage Systems Division, it applied the etching texture technology originally developed by its Process

Technology Lab (a corporate lab) to control the surface of MR heads. Second, Hitachi tried to use its high-speed ECC (error code correction) technology that was originally developed by Hitachi for telecomunication devices. They improved the code-processing LSIs with the help of engineers of the Semiconductor Division. Engineers of head, media, LSI groups of the Advanced Technology Development Center also conducted experimentation through collaboration with the Central Research Lab.:

> “We built many ‘semi-prototypes’ to explore MR drive technology. These usually did not work, so we often had to send the prototype from the Advanced Technology Development Center to the Product Development Group, and back again, along with much communication between the departments. While doing this, the division of labor between the two sometimes disappeared, and engineers sometimes worked in the other’s areas for weeks on end in a total effort to resolve the problems. We also had formal inter-departmental meetings once a month, involving all managers. We also created a ‘project team room’, where the walls were covered with data on experiments, facilitating discussion there. There were informal inter-departmental meetings almost every day in the room.”

IBM’s Organizational Re-configuration

The costs of firms being caught in the modularity trap in the hard disk drive industry have risen due to the organizational reconfiguration of IBM. Leveraging its technology advantage in MR heads, IBM reversed its course of many years, and aggressively entered the OEM disk drive market, selling its MR-based drives to numerous computer makers. They have been particularly effective in penetrating the 2.5” hard disk drive market, where their market share now has reached over 50% (Disk/Trend, 1998). While selling MR components gives other drive makers access to leading edge technology, IBM likely believes that the gains from the expanded volumes it garners from selling its components outweigh whatever costs are incurred from having competing firms using its component technology. And of course, IBM’s drive division benefits from this greater component volume in the form of lower costs for the heads it uses, making its drives still more competitive.

The benefits of this reconfiguration are already becoming apparent. IBM’s OEM market sales of disk drives, all of which employed IBM’s MR heads, grew from nearly zero in 1992 to almost $3 billion by 1997 (Disk/Trend, 1998). IBM’s new approach means that competitors cannot rely on IBM to forego market opportunities outside of its own systems business. If competitors fail to keep pace with IBM in technology, they are now punished by IBM’s willingness to deploy its technology across the industry. This deprives Japanese and other US firms of unserved markets for their MR technology. As a result, these firms have found it harder to gain sufficient volume to cover their own R&D costs.

As we have discussed, IBM’s organizational strategy has drifted in and out of alignment with the phase state of its head technology. This movement is depicted in Figure 4 below.   IBM has done well when its technology and its organization are in alignment, while it has suffered when the two have drifted apart. This suggests that there is no ‘best’ organizational configuration for pursuing technology through the various phase shifts. Instead, organizations must invest in systems level knowledge and integration during integral phases, while pursuing decentralized buying and selling of technology during modular phases.

[Figure 4 about here]

Strategies for Stimulating the Alignment of Organization and Technology Phase

We are arguing that firms need to develop greater organizational flexibility, in order to align their organizations with the phases of their technology. We are not alone in this contention (see Tushman and O'Reilly (1997) and Christensen (1997) for other arguments for the need for greater flexibility). Our own story about IBM, though, suggests that such flexibility is difficult to realize. IBM's organizational strategy has drifted in and out of alignment with the phase state of its technology, suggesting that its organization exhibits strong inertia.

There is an extensive literature on the inertia of organizations (Hannan and Freeman, 1977; Hannan and Carroll, 1989), demonstrating that such inertia is widespread. This may indicate that our model is too ambitious in suggesting that organizations can adapt to phase shifts in technology. While we recognize the severity of organizational inertia, we believe that organizations nonetheless can develop dynamic capabilities (Teece et al, 1997) that can enable proactive response to shifts in technology. We view Fujitsu as an example of a disk drive firm that has achieved a fair degree of agility in aligning its organization with the phases of its technology, as a result of important investments it has made in its capabilities.

When IBM made its MR technology announcement in 1992, Fujitsu was already planning its own research and development response. From their central research laboratory in Atsugi, they already had extensive basic research into MR materials. This group had been tracking earlier IBM activities in MR, and had already begun to research the properties of this material. However, being integrated back into research does not auomatically promise a firm an escape from the modularity trap. Since the technology phase shift are cyclical phenomena, it is critical for a firm to develop dynamic capabilities to utilize its integrated assets for stimulating the alignment of its organization and changing technology phases.

From this point of view, Fujitsu may provide a good example of a firm with such dynamic capabilities. Not only being integrated, Fujitsu's organizational stategy was characterized by its way of managing the division of labor for developing MR drives. There were two key characteristics underlying Fujitsu's integrated organizational strategy. First was the flexible categorization of engineering activities. Though Fujitsu possessed a variety of engineering capabilities including basic research, components development, components manufacturing and HDD assembly, its definition of each engineering activity was not so rigid. To the contrary, Fujitsu's categorization of activities was rather flexible so as to make it possible to adapt to technology phase shifts. As we have seen, Fujitsu transferred people from this central lab to Fujitsu's Storage Technology Laboratories, in Atsugi and Kawasaki. The number of engineers in the Storage Technology Laboratories almost doubled in one year's time, while the number of engineers in the HDD development division grew by more than half. Overall, the total number of engineers grew by over 60% in one year an alert and agile response to a phase shift in the head technology. Also, Fujitsu repeatedly used the co-located, cross-departmental working groups at the Storage Component Division for physically sharing protptype-based experiments in order to identify and resolve the interdependency problems, which diminished the functional boundary between engineers. Such co-located working groups enhanced the flexibility of the boundary definition of each engineering activity, enabling engineers with different functional tasks to focus on technical interdependencies at the drive system level.

Second, the ‘system-based differentiation’ was another key characteristics underlying Fujitsu’s R&D organization (Kusunoki, 1999). Not only being flexible, Fujitsu’s categorization of engineering activities was based on different perspectives on the drive system across a time dimension, rather than on conventional functional differentiation. Its different R&D units such as the Fujitsu Central Lab, the Storage Technology Lab, the Storage Component Division, and the Hard Disk Drive Development Division were not simply differentiated along the functional dimension, nor were they intended to optimise engineering activities within their functional domains, e.g, research, components design, components manufacturing, drive design, assembly and so forth. In fact, each lab or division focused on a its unique time-perspective on the whole HDD system. For example, engineers of the Storage Technology Lab focused their activities on Fujitsu’s future generation HDDs, the Storage Component Division on the next generation or high-end HDDs, while the Hard Disk Drive Development Division targeted the current generation HDDs. Each lab or division thus possessed not only functional knowledge but also system-level knowledge of HDD that was differentiated along a time horizon. Hence, each possessed particular knowledge for resolving technical interdependencies within itself even before actual coordination and communication for system-level problem-solving. In this sense, Fujitsu’s problem-solving across departmental boundaries at the working group was more than cross-functional integration. It was rather cross-perspective integration in which different perspectives on the HDD systems blended into the problem-solving of technical interdependencies. This system-based dimension of organizational differentiation facilitated each division’s focus on the system-level interdependencies as well as to generete an effective and efficient approach of resolving the interdependencies. One manager of Fujitsu noted:

> “Even when I was struggling with the MR technology at the Storage Technology Lab, I did not have the notion that I was doing it for MR heads alone. Rather, what I wanted to do was to develop and commercialize a totally new MR drive. My effort was not limited to the head itself. I was always thinking how we could make our HDDs better by using the MR heads under development. In this sense, there was no sharp distinction between our advanced engineering at the seemingly component-level and drive development in the HDD Division. So, it was very natural for us to get together and collaborate in the working group at the Storage Component Division. However, our perspective on HDDs were more future oriented, while the division guys concentrated on the design for a coming model.”

The ability to access and transfer advanced technology - and the people who developed it - proved crucial in Fujitsu’s ability to avoid the modularity trap than befell NEC and Toshiba. It enabled them to begin MR development sooner, to get initial prototypes developed faster, creatively resolve technical issues across departmental boundaries, and to ship working products two years ahead of the other two firms. Fujitsu’s flexible categorization and system-based differentiation of R&D activities constitute two valuable capabilities that provided it the ability to respond to technical changes that frustrated other firms that lacked these capabilities. If Fujitsu’s engineering activities had been ridigly defined, functional boundaries between advanced engineering, components design and drive design could have hinder engineers to focus on developing integral knowledge, which might have result in the modularity trap even under its integrated organizational strategy.

This, however, is only half of the organizational agility required in our model. The other imperative is to be able to adjust to technology phase shifts where the technology becomes more modular, and requires greater decentralization to exploit the technology. How can a firm with the above capabilities avoid being inhibited by them when the technology phase shift obliges them to do so? How can they escape the alternate trap, the integrality trap?

Fujitsu again may serve as an illustration that such escape is possible. As Fujitsu developed its first magneto-resistive (MR) heads internally and then created its first drives using MR heads, it deliberately shared its MR technology with a long-standing head supplier, TDK. While it continued to develop MR heads internally, it carefully nurtured TDK as a second source of MR technology. In the early stage of MR technology development (1992), TDK had not committed itself to MR heads, due to its technological difficulty. It was Fijitsu that encouraged TDK to enter the MR head business. The Fujitsu Lab first disclosed its experimental data on its MR heads to TDK, and then started intensive and extensive communication with engineers of TDK. Supported by Fujitsu, TDK developed many prototypes of MR heads for Fujitsu. The Storage Technology Lab tested and evaluated the samples from TDK in Fujitsu's drives. Fujitsu also had a strong commitment to TDK in terms of its business. Fujitsu purchased all of the TDK's first volume production of MR heads. For the first model of its MR drives, Fujitsu purchased approximately half of its head requirements from TDK, making the other half internally. Why would Fujitsu voluntarily disclose the results of many tens of millions of dollars of research to an outside supplier, who would then sell heads based on that technology to competing disk drive manufacturers?

We see three related reasons for Fujitsu's decision, all of which have the effect of avoiding the integrality trap. One, Fujitsu was proactively recruiting a second source to its own internal head manufacturing division. This outside source would provide rivalry

(Asunama, 1992) to the internal operation, and force it to remain competitive. Two, Fujitsu acquired extensive process technology know-how from TDK as a result of sharing its MR technology. Since quite subtle factors in the manufacturing process had substantial influences upon the quality of MR heads, Fujitsu could benefit from learning TDK's know-how in order to improve its MR drives, especially when resolving the complicated interfaces between heads and other components. This increased the yields and reduced the costs of Fujitsu's internal head division. Three, Fujitsu felt it would benefit directly from the increased volumes its supplier would obtain from other companies. In addition, this would lower the benchmark costs for its internal division yet again (Tatsuta and Adachi, 1998), creating an ongoing impetus for further internal cost reduction.

The division of activities between Fujitsu and external suppliers was also flexible. TDK was not simply an outside head supplier for Fujitsu, nor was the the division of activities rigidly fixed. The role of TDK for gradually changed in the process of MR drive development, which was based on mutual commitment and trust created through long-term colloaboration. As for the heads sourcing, Fujitsu's strategy may appear to be 'outsourcing,' but its dynanic division of activities with TDK enabled it to escape from the integrality trap in which integrated firms without dynamnic capabilities to benefit from their 'integrality' were often caught.

Fujitsu also empowered its hard disk drive division to aggressively pursue outside sales of disk drives to other systems companies. These policies meant that, at both the drive level and the systems level, Fujitsu was simultaneously buying technology from outside companies, and selling its technology to outside companies. This approach is quite decentralized, forcing each division within Fujitsu to stand on its own value added, and unshackling Fujitsu's components and disk drives from impediments from the corporate level.

Fujitsu's strategies build upon long standing investments in research, flexible categorization of boundaries of inside and outside engineering activities, system-based differentiation of R&D organization, and proactive decentralization policies. These appear to have conferred some agility upon it. Firms pursuing virtual strategies such as NEC, Toshiba, Western Digital, and Maxtor had no such dynamic capabilities, severely curtailing their ability to incorporate MR technology in its integral phase state.

Conclusion

We think that technology evolves in cycles, emerging initially in an integral form in which the various technological interdependencies are quite opaque. Gradually, these interactions become well understood, after extensive processes of experimentation, trial and error. This understanding causes the character of the technology to become modular in its nature. However, further research and discovery can generate new breakthroughs that restart the cycle again, and such breakthroughs are often triggered by particular modular innovations.

To profit from innovation in these different phases of technology, we offered a model of how firms needed to align their organizations with the character of the technology they are pursuing. Modular technology phases required decentralized or virtual organizational approaches that coordinated technical adjustments through the market to capture value from innovation. Integral phases required much more centralized or integrated organizational structures that leveraged managerial processes to coordinate poorly understood interdependencies inside the firm.

Firms that did not so align themselves were at risk of falling into one of two organizational traps. One was an integrality trap, where a centralized firm continued to rely on managerial coordination in a modular phase of technology to manage its technology development. The other trap was a modularity trap, where firms that had achieved success through decentralized coordination through the market continued to rely on those methods for resolving integral technology issues.

Given the recent enthusiasm for virtual firms, we think it worth emphasizing this latter trap. Firms such as Toshiba and NEC relied on outside suppliers capabilities strategies to incorporate MR technology, effectively ignoring the import of the technology phase shift of MR towards greater integrality. The lack of strong systems integration knowledge, combined with deep component knowledge, caused them to underestimate the challenge of the MR technology shift, and forced them to rely on outside suppliers to respond to the challenge. These outsider firms similarly lacked the required systems knowledge. The resulting problems in coordination resulted in late shipments of the technology, leading to the loss of market share for Toshiba, and the decision of NEC to stop the design of future disk drives. Firms such as IBM and Fujitsu, who possessed the technical capability at the systems and component levels, and employed a centralized organizational strategy to manage the technology transition of disk drive heads towards an integral phase, have been able to profit handsomely from their competitors'weaknesses. As MR technology becomes well established, both firms are also adopting flexible organizational strategies that will allow them to continue to profit from this technology.

Virtual organizations are widely believed to be effective in pursuing speed and agility. This is certainly true in some industries where technology is in a modular phase. If technology is rather integral like the automobile industry, integrated organizational strategies work better to profit from innovation opportunities. Similarly, industries where the technology is stably modular may benefit more from delayed, horizontally organized, more virtual approaches.

While this contingent perspective has been a common understanding among academic sholar and practitioners, our point of view emphasizes that such a static contingency framework may overlook the dynamic aspects of technology. Even if technology is currently in a modular phase, it can move back to integral, and vice versa. The technology phase-shifts can bring about considerable impacts on firms competitiveness. Our concept of the modularity trap may therefore carry an important insight for the virtuousness of virtual firms.

Notes:

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[1] We adopt the term “integral” to highlight the organizational implications of this type of technology, and to dispel any potential confusion between “systemic” technology and “systems” technology that might arise for readers with engineering and scientific backgrounds. In an earlier paper, one of us termed this type of technology ‘systemic’ (Chesbrough and Teece, 1996), which might generate such confusion.

[2] We provide one example of this cycling in our discussion of MR head technology in hard disk drives below.

[3] Our account of the introduction of thin film heads in this section draws heavily from Christensen’s extensive research program in hard disk drives. See Christensen (1992a; 1992b; 1993; 1997) and Christensen and Chesbrough (1999).

[4] Of course, it took some time to ascertain that ESD was responsible for many of these failures, because the test procedures themselves had to be modified, and so “failures” were subject to the usual Type I and Type II error problems.

Figure 4:
IBM’s Movement Along the
Technology-Organization Alignment Matrix

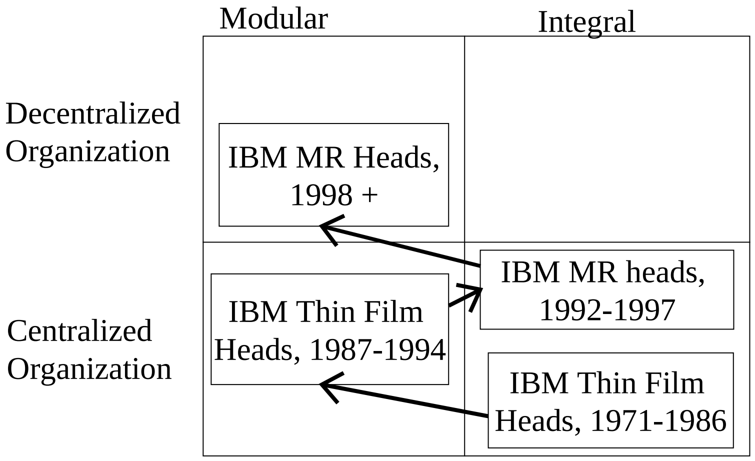


Figure 1:
Technology-Organization Alignment Matrix

	Modular	Integral
Decentralized Organization	Proper Alignment Value realized only within technology layer No inefficient interactions	Misalignment Can't manage interactions Insufficient infrastructure
Centralized Organization	Misalignment Unnecessary internal coordination Reduced scale economies	Proper Alignment Value realized through the system Effective coordination of undefined interactions

Figure 2   Technology Phase-Shifts

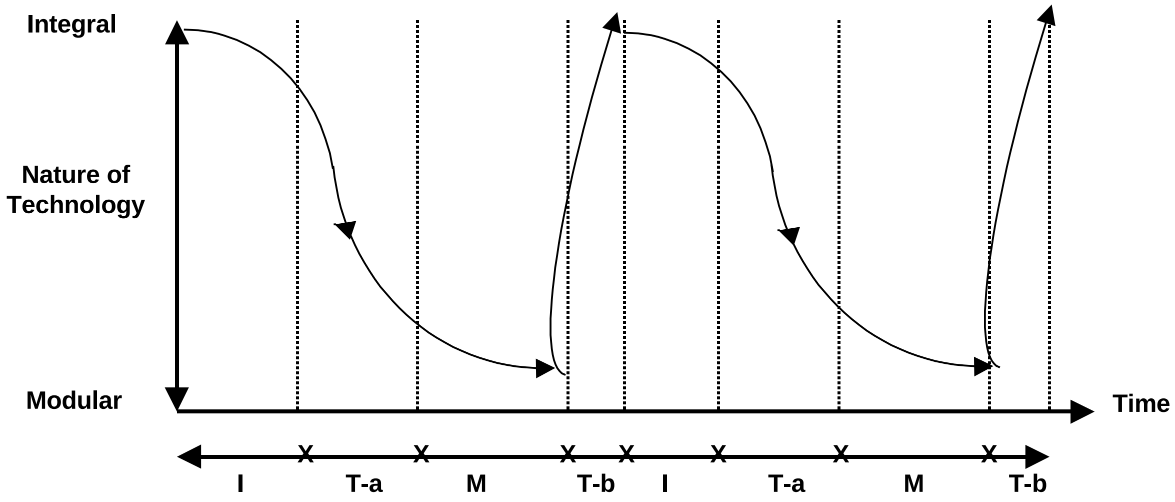
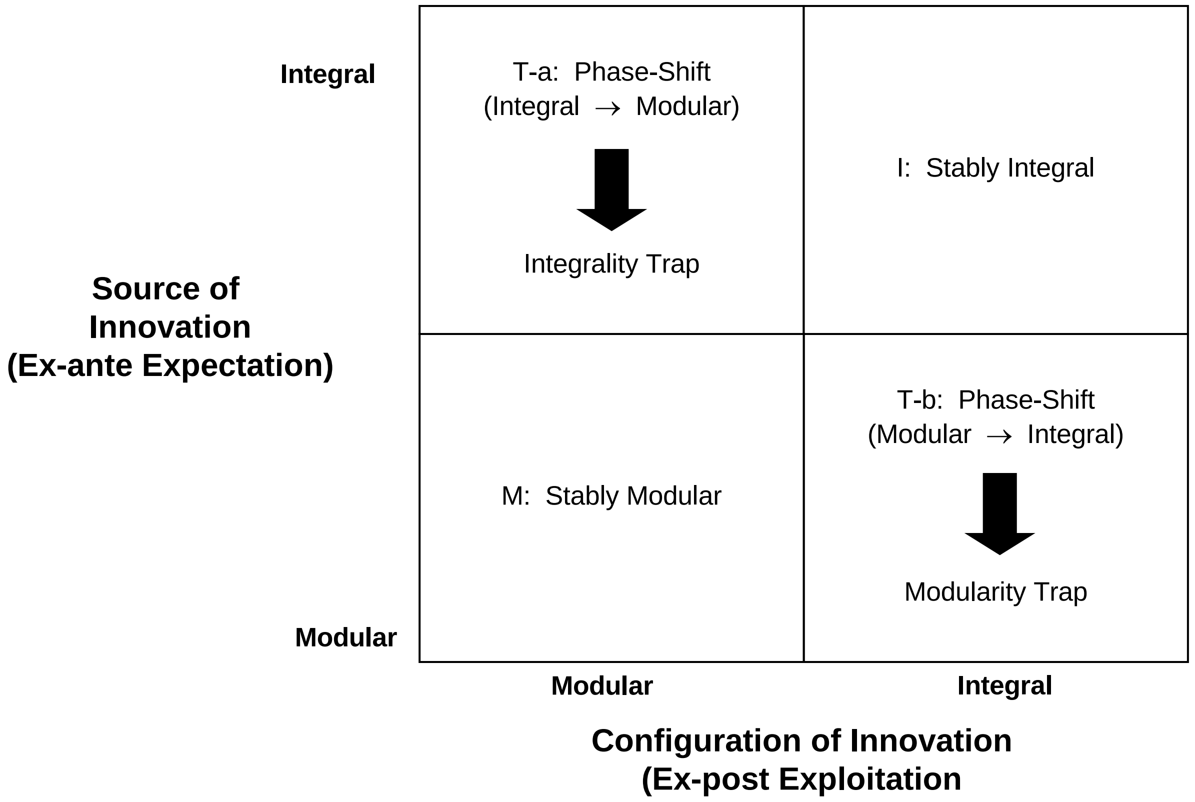


Figure 3 Two Views of Innovation and Technology Phase-Shifts



	Modular	Integral
Integral	T-a: Phase-Shift (Integral → Modular) Integrality Trap	I: Stably Integral
Modular	M: Stably Modular	T-b: Phase-Shift (Modular → Integral) Modularity Trap

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