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10 The Modularity Trap: Innovation, Technology Phase Shifts and the Resulting Limits of Virtual Organizations*

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Introduction

Scholars have long noted that the technology of the firm shapes the organization of that firm (Burns and Stalker, 1961, and 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, and 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, and 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 to observe the effects of change over a relatively short period of time. Technology provides, and indeed requires, explicitly dynamic approaches to managing knowledge, as Fiona Murray (among others) argues in Chapter 9.

This chapter builds on the prior research by developing a contingency framework firms may use 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 call 'integral' (defined below), to an opposite type, which we call 'modular' (also defined below), then cycles back. As the technology shifts from one phase to the other, the optimal organizational configuration of the firm must also shift if it is to continue to capture value from its innovation activities.

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However, the optimal alignment to a technology phase shift can be quite difficult, and often firms fall into organizational misalignment. Here we develop a conceptual framework of such organizational traps that helps explain how and why a firm fails to capture value from innovation after 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 the 'modularity trap', which is when a firm that has successfully aligned its organization with a modular phase of technology encounters difficulty 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 via the marketplace, where independent firms come together to buy and sell technology and the components that are used to make the various items (Chesbrough and Teece, 1996). As this strategy can maximize flexibility and responsiveness in a changing marketplace, the virtual organization appears to provide a powerful and predominant model in industries that produce PCs, biotechnology, semiconductors and other technology. In these industries, many large, integrated firms have been outperformed by smaller, more focused competitors.

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. For highly focused firms, this shift can create a serious problem, which we call the '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 technology that rearranges the boundaries of existing technology. Their single-minded focus within a specific configuration of technology then becomes a significant liability. We will explain our reasoning about these technology shifts and the resulting organizational responses below, then illustrate their impact with examples from the Japanese hard disk drive industry.

Technology Phase Shifts and the Need for Organizational Alignment

When a new technology emerges, technological development in the industry is usually in a phase we term 'integral' (following Christensen and Chesbrough, 1999).[1] Here, the technical information about how the different elements of a system function together is not well defined and interactions between elements are poorly understood. The new technology 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, whereby new components simply plug into the existing architectures without a hitch (Henderson and Clark, 1990).

Because the interactions between elements of this integral technology is poorly understood, developing it further is more complicated. Under these conditions, intermediate markets do not function effectively and can even be hazardous. A customer cannot fully specify their requirements to a supplier. The supplier can develop a product that meets the literal specification, only to have the customer return it because it does not work in the customer's product. Independent companies may reasonably differ about the cause of such a problem. Each may want the other to do more (and bear more of the costs) to resolve it. Customers and suppliers may also wish to avoid highly specific solutions to a particular problem for fear of being locked into doing business with 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 close coordination and facilitate rapid mutual adjustment between pieces of interdependent technology, administrative coordination outside the market is required to develop a technology effectively. An internal or captive supplier of interdependent pieces of component technology has three general advantages over firms that coordinate via the market. One advantage is having superior access to information. The second advantage is weaker incentives to exploit temporary advantages inside the firm. The third advantage is tighter appropriability of the returns generated by the solutions to technical problems. We consider each of these in turn.

The information advantage arises from the fact that there is less 'impacted information' (Williamson, 1975) – that is, more information can be shared more quickly within the firm than can be shared between firms. Firms have access to even very detailed findings within their own 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, because employees usually expect to stay at a firm over time, they have an interest in cooperating today in return for receiving cooperation tomorrow on another project. Arm's-length coordination via the market has none of these advantages. One firm has no legal right to view the results of tests conducted at another firm, and firms can choose to act strategically when deciding what information to share and what information to withhold. Moreover, the very fact of dealing at arm's length means that neither party can be assured of working with the other in the future. Each firm may

manoeuvre to encourage other suppliers or customers to create greater freedom of action to work with other companies in the future, in part by 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 another are pooled together in the firm's overall stock price. Relative to firms transacting via 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 more attenuated than they would be for independent companies.

The final advantage is that of tighter appropriability (Teece, 1986). Divisions within a firm that work together to reduce complicated technical interdependencies can be fairly certain that they will benefit from the results. The likelihood that one division will hold up another 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 renegotiation later on.

For these reasons, firms that follow integrated organizational strategies will match their internal organization better to the characteristics of integral technology. When innovation activities are integrated, firms can better manage the interactions between technical elements and share information freely without worrying about distortions in subsequent bargaining over the terms of exchange between business 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, and Anderson and Tushman, 1990). These standards permit even complicated 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 added value. When rival suppliers with interchangeable products discipline one another to promote strong competition within these standards, the result is more rapid technological advancement and lower prices to systems customers.

In these circumstances, virtual firms are indeed more 'virtuous' (Chesbrough and Teece, 1996) than 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 technical standards. These standards codify the technological interactions, leaving relatively little technical ambiguity. The establishment of standards permits numerous firms to experiment with a variety of implementations, and the resulting diversity far exceeds what could be produced inside a single firm's walls. The very basis of competition shifts from constructing complicated systems with integral designs to more horizontal competition within individual layers of technology, bounded by these standards.

The incentive within firms remains 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 an alternative source of technology should any firm attempt to hold up another. As markets can now function effectively to coordinate technical development within these standards, high-powered incentives lead to more advanced technology sooner. The presence of alternative sources similarly resolves potential appropriability problems, because suppliers have other customers and customers have other suppliers. Each can only expect to profit from the value added by its own technology.

Firms that follow virtual organizational strategies effectively match their internal organization to these modular technological characteristics. For virtual firms, focusing on a single layer of technology harnesses the strong incentives and high volumes available via 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 when the technology is in a modular phase. This decentralized organizational strategy must enable units within the firm to buy and sell components independently in the modular technology markets. In particular, decentralized organizations eschew corporate dictates to use captive sources when market conditions make this choice unwise. Similarly, they 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 an organization to reconfigure itself organizationally in order to effectively develop a technology. An important implication of the model is that the organizational strategies that integrated firms need to employ to appropriate the value of the technology they develop in their 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 of a 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 evaluate the condition of the technology on which their business is based and then adopt appropriate organizational policies and structures based on that evaluation. Firms that align their structures well will profit from their innovation

	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 in the system Effective coordination of undefined interactions

Figure 10.1 *Technology–organization alignment matrix*

activities, while firms that do not will fall into the organizational traps that we describe below. These traps will frustrate their ability to capture value from their innovation investments.

The link between organizational alignment and technological phase can be depicted in a matrix, shown in Figure 10.1.

Figure 10.1 displays the interactions 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 links 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 in the ability of internal coordination mechanisms to manage the complicated 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 lower left and upper right quadrants indicate cases of misalignment, or organizational traps, where value can be dissipated owing to an inappropriate organizational approach to the technology. These misalignments are described and illustrated in detail below, with recent research findings from the Japanese hard disk drive industry.

The Shift to a Modular Phase and the Integrality Trap

The history of much technology reveals that the character of it is that it can cycle from very integral states to very modular states, and back, as shown

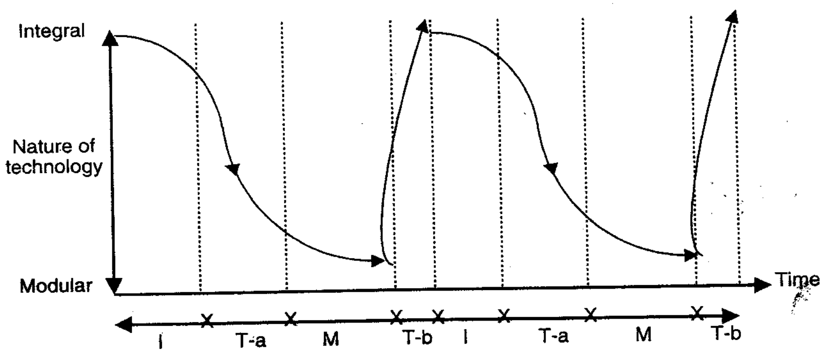

Figure 10.2 *Technology phase shifts*

in Figure 10.2 (an example of this is given below in the discussion of disk drives). In the early stage of an industry, technology underlying the product system is usually integral, implicitly encompassing substantial interdependencies between elements. At this time, how different technological elements interact with 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. It is tacit and usually embedded in one's experience as know-how (Nonaka and Takeuchi, 1995).

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, based on new knowledge about how to coordinate interdependent technological elements and components within a product system, improves functionality and quality and reduces the cost of the product system. Given the tacit, context-dependent nature of integrative knowledge, however, realizing integral innovation requires a series of experiments, trial and error and continuous learning by doing, which takes a long time. By going through these experiences, firms gradually come to understand how the different technological elements and components that make up the product system interact with each other. They may develop tools, specialized equipment, testing procedures and simulations to better understand these complexities. As a result, technological interdependencies between elements lessen and interfaces between components are 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 technology 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 inside the firm.

If a firm proves unable to adapt its organizational configuration to the dictates of the phase of its technology, it will be caught in an 'organization trap'. If a firm remains integrated when a technology becomes more modular, it will be caught in an 'integrality trap' where it must rely on administrative mechanisms to accomplish technical coordination that other firms are able to accomplish in the market (see the lower left quadrant of Figure 10.1). Such misaligned firms continue to pursue internal coordination activities when these activities could be well managed via the technical interfaces and standards in the market.

Why are firms often caught in the integrality trap? The mechanism underlying this trap is closely related to the paradox that integral innovation triggers the shift to a 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) is critical for classifying innovations. It is rather misleading to classify an innovation by looking only at its *ex post facto* configuration along the modular–integral dimension. Each innovation is, by nature, a dynamic process: a firm first perceives the source of an innovation and how it might lead to a better product and then exploits the source to realize an innovation with a particular configuration. This is shown in Figure 10.3.

Thus, an innovation can be viewed from two different angles. The horizontal dimension captures the *ex post facto* configuration of an innovation realized. As we have discussed, this dimension determines effective organizational alignments to exploit the value from innovation. The vertical dimension captures the source of the innovation, whether it consists of particular elements or by the combination of those elements. Framed in this way, an innovation can be characterized by the interaction between its source (*ex ante* expectation) and its configuration (*ex post facto* exploitation). Viewing an innovation as the interaction is important because an innovation that has its source in the progression 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. On 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

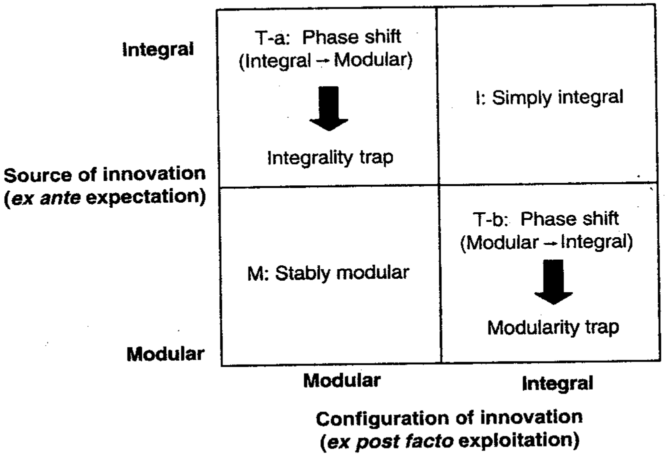

Figure 10.3 *Two views of innovation and technology phase shifts*

a configuration of innovation are typically observed when technology shifts from integral to modular or from modular to integral.

In a phase where technology is stably integral (as in Phase I in Figure 10.2), a firm will find a source of innovation as integral (a possible better way to combine elements), then it may expoit the opportunity for developing a better product via 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 facto* configuration of the innovation (see the upper right quadrant of Figure 10.3). As firms expand their knowledge of the interdependencies of elements and components in the process of making integral innovations, technology will be in a transition phase (as in Phase T-a in Figure 10.2), gradually shifting towards the modular. In this state (the upper left quadrant in Figure 10.3), some firms may exploit the opportunity derived from preceding 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, 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 prevent them from aligning their innovation activities with modular innovation, thus creating an organizational inertia that results in the integrality trap.

When Technology Shifts to an Integral Phase: the Modularity Trap

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 do not also become more centralized organizationally. If a firm remains virtual as its technology shifts to a integral phase, a 'modularity trap' ensues, which is when a firm lacks the systems and experience to comprehend the new interdependencies necessary to develop the technology. The firm is no longer able to specify its needs and requirements adequately to its outside suppliers, so its familiar problem-solving routines are no longer effective. Unlike in internally organized firms, the supply chain linking the horizontal technology layers in the virtual firm is unable to achieve the coordination necessary to develop the technology.

The logic underlying this modularity trap comes from another paradox. This is that the technological shift to the integral phase can often be triggered by modular innovation. After the phase transition from integral to modular (Phase T-a in Figure 10.2), technology goes into the stably modular phase (Phase M, also in Figure 10.2). In this stage, innovation becomes 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 quadrant of Figure 4.3). However, modular innovation can sometimes reveal the need to deconstruct established ways of combining technological elements and components and, consequently, may force firms to develop new integral knowledge. Such disruptive modular innovation can result in a technology phase shift back to integral, where it again becomes unclear how different technological elements interact with each other (Phase T-b in Figure 2). At this time, the *ex post facto* configuration of innovation should be integral, while the source of innovation itself is still modular (as shown in the lower right quadrant of Figure 10.3). This distortion in the process of innovation can invite firms into the modularity trap (which is depicted in the upper right quadrant of Figure 10.1).

Firms that have enjoyed the advantages of virtual organization in the modular phase of technology will encounter great difficulties in this situation. These firms may have difficulty exploiting value from the modular innovation because it will not contribute to developing a better product without substantial coordination and interaction between technological elements.

The modularity trap is a real problem for firms with virtual organization strategies for the following two reasons. First, it would seem rational – even easy – for such firms to respond to the modular innovation opportunity by retaining their existing virtual organization. Because the innovation source lies in a specific technological element or component, the opportunity it presents seems clear. Furthermore, firms following a virtual organization approach can quickly and easily access components of a modular innovation from independent firms that began making and selling the components during the preceding modular phase. Hence, for virtual firms, the modular innovation appears to be more of an opportunity than a threat. Given the mechanism of the phase shift back to integral, virtual firms will remain virtual in order to take advantage of the abilities they have already developed. The modularity trap will become apparent only after they encounter *ex post facto* problems of interdependency and interaction between components.

Second, and very important, a technology shift back to the integral phase usually occurs over a much shorter time span than a shift to the modular phase; modularization takes a relatively long time because of the incremental nature of progress in integral knowledge. A shift back to the integral phase is triggered by a change in modular knowledge that is more explicit and context-independent. Once a firm introduces a modular innovation that requires major changes in how elements and components interact with each other, the stable interfaces between elements are broken immediately and technology moves back towards an integral phase.

This rapid shift makes it even easier for firms to fall into the modularity trap and 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 to solve the coordination problems, this choice may result in a serious competitive penalty because creating integral knowledge takes a long time. Alternatively, they may rely on the problem-solving efforts of independent suppliers. However, doing so again raises the hazards of specificity and bargaining costs between the parties, making coordination still more difficult. Thus, once virtual firms fall into the modularity trap, there is no clear way out of it.

Technology Shifts and Organizational Misalignment in the Japanese Hard Disk Drive Industry: Thin Film Heads

We now examine the issues described above by looking at field research we conducted in the Japanese hard disk drive (HDD) market. The HDD industry has experienced technology phase shifts that we believe have 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 that control the drive's operation and its interface with the computer. Although each of these component elements has evolved rapidly over the past few decades, here we focus primarily on the evolution of disk drive head technology.[2]

In the 1960s and 1970s, the HDD industry employed iron or ferrite heads that were mechanically ground to the correct tolerances for integration with iron-oxide media into a HDD. This technology was in a modular state, as the mechanical and electrical properties of ferrite heads were becoming well understood. Many companies at this time used outside suppliers and new suppliers were able to offer their heads to drive manufacturers.

There was a problem, however. The known characteristics of ferrite heads indicated that a new type of head would need to be developed if the industry were to continue to advance its technology. In anticipation of this eventual limit, IBM began developing prototype thin film heads at its 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 research and development activity in other firms in that same year.

However, the new developments also caused problems. Using thin film material in a HDD required making numerous and extensive changes in other parts of the drive. The design of the head depended both on the design of other components in the system and the architecture of the system itself. Also, 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 from that used with the ferrite technology was used. The new head required differences in the disk media in order to reliably read and write data with the new material. Changes in the methods of error correction also 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 those 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, the design of the head stack, the media coating or surface, the read channel electronics or 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. Although they were able to make a number of incremental improvements to ferrite head technology that extended its life 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 disk drive manufacturers. 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 by revising its head designs, new problems cropped up in the head–disk interface, the disk surface and the associated electronics.

We view this situation as a 'modularity trap' that engulfed AMC and its drive customers. Independent head companies in this era knew how to engineer well-characterized technology such as ferrite heads and competed effectively with that technology. When that technology had matured and was starting to become obsolete, however, those same firms did not 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 contrast to AMC, IBM clearly benefited from its organizational strategy at this time in the industry. Because of its integrated organization and impressive abilities in research and development, it was able to establish a lead of many years in the deployment of thin film heads in HDDs. 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 because the integral nature of thin film heads at the time precluded the creation of an active merchant market for them for many years to come.

The Phase Shift in Thin Film Head Technology Towards Modularity

Eventually, the mysterious attributes of thin film heads were sorted out by HDD makers and independent component manufacturers (many of whom hired key engineers from IBM, 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 were stabilized, test equipment companies developed tools to verify these characterizations and suppliers could be coordinated by their conformance to these characterizations. Joining AMC was new entrant 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 these and other independent firms making high-quality heads in very high volume, along with the parallel development of other companies in the United States and Japan mastering the thin film technology, meant that IBM no longer enjoyed a proprietary technological edge attributable 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 during 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 volume of head production to its internal needs. IBM's internal volume also suffered from other problems in its drive business at the time and resulted in rather low volumes (see Christensen 1992 and 1993). As a result, IBM became 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 IBM produced fewer of them, these heads were more expensive than those used by IBM's drive competitors. This cost penalty was compounded by a second effect. Because IBM could not sell its heads to other companies, it could not increase its production volumes in order to reduce its costs. 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 HDD industry meant that thin film technology itself would encounter limits as well. IBM's research labs were developing a new type of head technology called 'magneto-resistive' (MR). MR heads represented another tremendous advance beyond thin film heads that promised to increase the potential recording density of disk drives tenfold, but, again, its initial character was 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' (*San Francisco Chronicle*, 1992).

As with the initial thin film heads, the established design rules and models had to be thrown out. Once again, new design problems emerged.

Two common problems were electrostatic discharge (ESD) and thermal asperities (TAs), both of which illustrate the interdependencies of integral technology.

ESD was commonly encountered in the disk drive manufacturing process and every company had learned to protect the drive heads and drive electronics from it. What was new was the extraordinary sensitivity of MR heads to even minute exposures to ESD. An MR head could be processed through to completion, tested and then integrated into a HDD, but then fail to function in final test even though these processes had previously proved more than sufficient to manage ESD problems in thin film head designs. 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. Therefore 'failures' were subject to the usual Type I and Type II error problems. To resolve the problem, firms tried several changes – in the design of the head itself, the packaging for the head, the disk drive design and 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.

Thermal asperities are physical defects that the MR head creates in the spinning disk. This new problem results 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 causes the particles at that portion of the disk to swell, so distorting the signal recorded at that spot on the disk. Normal error correction codes often cannot be used to 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 HDD technology had shifted back to an integral phase. Once again, independent head manufacturers and their disk drive customers had difficulty adapting to this new technology. Non-integrated US companies such as Western Digital and Maxtor, which 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 earning 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 in order to obtain sufficient capital to remain in business. Quantum recently discontinued its captive MR head production, which it had acquired from Digital in 1994. This was the largest factor in a charge to Quantum's earnings of $190 million (*Wall Street Journal*, 1999).

Japanese firms' responses to MR technology phase shift

US firms are not the only ones to have fallen into this trap. We explored the response of the four leading Japanese HDD firms (Fujitsu, Hitachi, NEC and Toshiba) to these technology phase shifts. We learned that NEC, after more than 20 years of designing disk drives, decided in May 1997 to discontinue current generations of drive design work in MR and, 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-inch HDDs, many of which were employed in its own notebook systems. Toshiba initially treated the advent of MR heads as a minor extension of earlier head technology. When Toshiba developed its first MR drive, there were no off-the-job/on-the-job training programmes for engineers to master MR technology. In fact, the first MR drive development programme did not even have a unique project code name. Toshiba's first MR drive was just another product development following its earlier HDDs with thin film heads. Considering that the HDD 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 an approach contributes to stable supply and cost reduction of components through competition between outside suppliers, as well as avoiding risks of investment into component development. (Kamimura, 1998)

However, Toshiba's virtual approach faced difficulties during the development of its MR drives. This same 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 percent 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 improve 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 we did. (Kamimura, 1998)

Though Toshiba's development engineers frequently communicated with suppliers by means of drawings and specifications, they did not have a working-level collaboration. When they faced problems, they relied heavily on the problem-solving efforts of each supplier. For example, when Toshiba encountered the TA problem, its engineers only attempted to control the level of particles in the drive assembly process. Indeed, 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's narrowed possible paths to solutions. For example, the correction of TA only on the head side inevitably took a very long time (between three and four months) because the manufacturing process of MR heads requires many complicated steps, like a semiconductor fabrication process.

Toshiba's difficulties with MR heads in its HDDs has caused the company to change head suppliers. As of June 1998, it had tried three different head vendors. In 1998, Toshiba began using MR heads from Headway, a US 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 requires a different pre-amplifier, but it is a standard component that can be easily purchased in the marketplace.

Although Toshiba has tried to solve the MR head-related problems while retaining its virtual organizational strategy, it is still struggling to resolve technical issues related to the MR technology. Toshiba did not ship MR drives until four years after IBM, and its market share in 2.5-inch drives fell by ten percentage points from 1996 to 1998, while IBM increased its market share in 2.5-inch drives by a corresponding amount (International Data Corporation, 1998).

Not every Japanese HDD firm fell into the modularity trap. For example, Fujitsu was able to master the MR technology more effectively by investing continuously in systems knowledge, materials and component technology in its R&D labs. When the first MR drives were introduced, four different labs were engaged in MR drive development. Fujitsu Laboratory, a corporate lab, conducted long-term, MR head-related materials research. In December of 1993, 35 engineers were transferred from Fujitsu Lab to a division lab (Storage Technology Lab), including ten engineers who focused on head technology. At that time, however, only five engineers specialized in MR technology, because using MR heads had been only one option among three different technical approaches. In 1992,

Fujitsu Lab also pursued thin film heads and vertical heads as well as MR heads for possible future technology. Starting with the five engineers with MR expertise, Fujitsu gradually mastered MR technology in a learning-by-doing fashion. One engineer described Fujitsu's approach in the early stage of MR head development:

> At that time, we had neither an off-the-job nor on-the-job training programme 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. (Interview with Fujitsu engineer)

On the division side (Storage Products Group), three units conducted MR drive development from different perspectives. The Storage Technology Lab focused on future technology for key components, including heads, media, large-scale integrated circuits (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 it develop key components, it also built the high-end, state-of-the-art HDDs that used these components, developing systems knowledge with them. The HDD Division was responsible for developing current generation HDDs with project teams, each of which was organized for a particular model. HDDs for desktop PCs and mobile PCs were manufactured in this division.

Fujitsu's integrated organizational strategy gave it mastery over the many interdependent elements in the new MR head disk drive. Its approach to solving the noise problem is a good example. Controlling noise level was a technically subtle problem because noise was embedded in a complicated manufacturing process unique to MR heads. Fujitsu first tried to control the noise by improving the manufacturing process, but this effort did not reduce the noise level sufficiently. Hence, the company went back to materials development, which needed research-oriented technology developed at the Fujitsu Lab. In intensive collaboration with the Storage Technology Lab, the development engineers decided to speed up 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 of heads and other parts of an HDD. Most of these technical problems were found only after assembling components into a prototype. Head engineers collaborated extensively with those on the drive side (who produced the mechanism and the LSI electronics) to coordinate the interdependencies.

Though the problem appeared on the head side, efforts on the drive side, such as 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 than to think 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 skeptical about relying on only the head suppliers to fix this problem, because they might define the problem too narrowly, which might limit their ability to find the most effective solution to the problem. (Sugihara, et al., 1998)

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 interdependency problems. Such working group meetings were held at least twice a month during the development of the MR drive. 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 alternative solutions. Because of the strong inter-dependencies of the head–media interface, our head guys and media guys usually worked together in the same room to solve these problems. (Sugihara, et al., 1998)

Hitachi possessed similar capabilities in its own corporate labs, such as the Central Research Lab, the Basic Research Lab and its product development divisions' labs and advanced development groups. In 1991, the Advanced Technology Development Centre was established in the Storage Systems Division, and 100 HDD-related engineers were transferred from a variety of corporate labs to the Centre for MR drive development. They 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 MR head manufacturing process, which resulted in considerable improvement in yield. 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 error code correction (ECC) technology, which was originally developed by Hitachi for telecommunications devices. It improved the code processing LSIs with the help of engineers from the Semiconductor Division. Engineers of head and media, as well as LSI groups of the Advanced Technology Development Centre, also conducted experimentation by collaborating 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 others' areas for weeks on end in a total effort to resolve the problems. We also had formal interdepartmental 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 interdepartmental meetings almost every day in the room. (Nagai, 1998)

IBM's organizational reconfiguration

The costs to firms of being caught in the modularity trap in the HDD industry have risen since the organizational reconfiguration of IBM that began in 1993. Leveraging its technology advantage in MR heads, IBM reversed its course of many years and aggressively entered the original equipment manufacturer (OEM) disk drive market in 1993, selling its MR-based drives to numerous computer makers. It has been particularly effective in penetrating the 2.5-inch HDD market, where its market share has reached over 50 per cent (Disk/Trend, 1998).

While selling MR components gives other drive makers access to leading-edge technology, IBM likely believes that the gains from its expanded

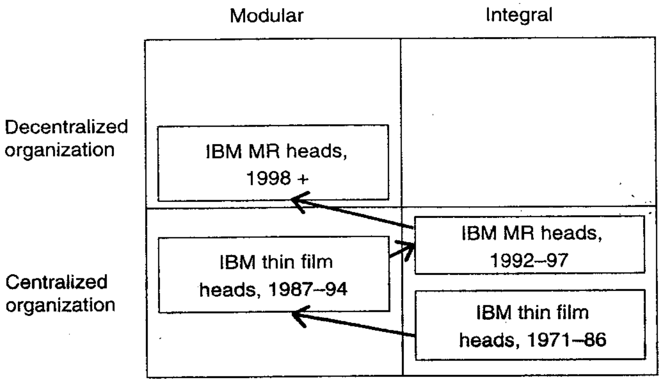

Figure 10.4 *IBM's movement along the technology–organization alignment matrix*

components sales outweigh the costs of having competing firms use its component technology. 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 apparent. IBM's OEM market sales of disk drives, all of which employed IBM's MR heads, grew from zero in 1992 to almost $3 billion in 1997 (Disk/Trend, 1998). IBM's new approach means that competitors cannot rely on IBM to ignore market opportunities outside of its own systems business. Competitors that failed to keep pace with IBM in technology are now being punished by IBM's willingness to deploy its technology across the industry to serve previously unserved markets. As a result, its competitors have found it difficult 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 of its head technology. This movement is depicted in Figure 10.4. IBM has done well when its technology and its organization are in alignment, and 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.

Strategies for Stimulating the Alignment of the Organization with the Phases of its Technology

We believe 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). The experience of IBM, though, suggests that such flexibility is difficult to realize. IBM's organizational strategy has drifted in and out of alignment with the phase of its technology, suggesting that its organization exhibits strong inertia.

There is extensive literature on the widespread inertia of organizations (Hannan and Freeman, 1989). Thus, our model may be too ambitious in suggesting that organizations can adapt to phase-shifts in technology. Although we recognize the severity of organizational inertia, we believe that organizations none the less can develop dynamic abilities that can enable proactive responses to shifts in technology (see Teece, Pisano and Shuen, 1997). We view Fujitsu as an example of a disk drive firm that fairly nimbly aligned its organization with the phases of its technology by making important investments in its abilities.

When IBM made its MR technology announcement in 1992, Fujitsu was already planning its own research and development response. In its central research laboratory in Atsugi, Fujitsu had conducted extensive basic research into MR materials. This group had been tracking earlier IBM activities in MR and had begun to research the properties of this material. However, being integrated back into research does not automatically guarantee that a firm will avoid the modularity trap. As the technology phase shifts are cyclical, it is critical for a firm to develop dynamic abilities 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 abilities. Besides being integrated, Fujitsu's organizational stategy was characterized by the way it managed the division of labour for developing MR drives. There were two key characteristics underlying Fujitsu's integrated organizational strategy. One was the flexible categorization of engineering activities. Though Fujitsu possessed a variety of engineering abilities, 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 flexible enough to adapt to technology phase shifts. As we have seen, Fujitsu transferred people from this central lab to its Storage Technology Laboratories in Atsugi and Kawasaki. The number of engineers in the Storage Technology Laboratories almost doubled during one year, 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 per cent in a single year in an alert and agile response to a phase shift in head technology. A second key feature of Fujitsu's organizational strategy was the co-location of cross-departmental working groups at the Storage Component Division, where they jointly conducted prototype-based experiments in order to identify and resolve the interdependency problems. This strategy expanded the boundaries of each engineering activity, enabling engineers with

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different functional tasks to focus on technical interdependencies at the drive system level.

Second, the 'system-based differentiation' was another key characteristic underlying Fujitsu's R&D organization (Kusunoki, 1997). In addition to being flexible, Fujitsu's categorization of engineering activities was based on different perspectives on the drive system over time, rather than on conventional functional differentiation. Its different R&D units, such as the Fujitsu Central Lab, Storage Technology Lab, Storage Component Division and HDD Development Division, were not simply differentiated along the functional dimension; nor were they intended to optimize engineering activities within their functional domains (research, components design, components manufacturing, drive design, assembly and so forth). In fact, each lab or division focused on 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 and the HDD 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 it undertook coordination and communication for system-level problem solving. In this sense, Fujitsu's problem solving across departmental boundaries in the working group was more than cross-functional integration. It was cross-perspective integration in which different perspectives on the HDD systems blended with the problem solving of technical interdependencies. This system-based dimension of organizational differentiation facilitated each division's focus on the system-level interdependencies and generated an effective and efficient approach to resolving the interdependency problems. 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 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 was more future-oriented, while the division guys concentrated on the design for a coming model. (Sugihara, et al., 1998)

The ability to access and transfer advanced technology – and the people who developed the technology – proved crucial in Fujitsu's ability to avoid the modularity trap that ensnared NEC and Toshiba. It enabled them to begin MR development sooner, get initial prototypes developed faster, creatively resolve technical issues across departmental boundaries and 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 with the ability to respond to technical changes that frustrated other firms that lacked these abilities. If Fujitsu's engineering activities had been rigidly defined, functional boundaries between advanced engineering, components design and drive design could have prevented engineers from developing integral knowledge, a problem that might have caused it to fall into the modularity trap despite 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 when the technology becomes more modular and requires greater decentralization to exploit. How can a firm with the above abilities avoid being inhibited by them when the technology phase shift obliges them to do so? How can they escape the other trap, the integrality trap?

Fujitsu again may serve as an illustration that escape is possible. As Fujitsu developed its first magneto-resistive 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 1992, in the early stage of MR technology development, TDK had not committed itself to MR heads because of their technological difficulty. It was Fujitsu 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 TDK engineers. Supported by Fujitsu, TDK developed many prototype MR heads for Fujitsu. The Storage Technology Lab tested and evaluated the samples from TDK in Fujitsu's drives. Fujitsu also had a strong business commitment to TDK. Fujitsu purchased all of TDK's first volume production of MR heads. For the first model of its MR drives, Fujitsu purchased approximately half of the heads it needed from TDK, and made 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 helped Fujitsu avoid the integrality trap. One, Fujitsu was proactively recruiting a second source for its own internal head manufacturing division. This outside source would provide rivalry to the internal operation (Asunama, 1992) and force it to remain competitive. Two, Fujitsu acquired extensive process technology know-how from TDK as a result of sharing its MR technology. As subtle factors in the manufacturing process had substantial influence on 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, the increased volumes Fujitsu's supplier would obtain from other companies would benefit Fujitsu by lowering 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 division of activities rigidly fixed. The role of TDK gradually changed in the process of MR drive development, which was based on mutual commitment and trust created by long-term collaboration. As for the sourcing of heads, Fujitsu's strategy may appear to have been 'outsourcing', but its dynamic division of activities with TDK enabled it to escape from the integrality trap in which integrated firms without dynamic abilities were often caught.

Fujitsu also empowered its HDD division to aggressively pursue outside sales of disk drives to other systems companies. Doing so meant that – at both the drive level and the systems level – Fujitsu was simultaneously buying technology from outside companies and selling its own to outside companies. This decentralized approach forced each division within Fujitsu to stand on its own value added feet and unshackled Fujitsu's components and disk drives from restraints at the corporate level.

Fujitsu's strategies build on 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 given the company some agility. Because firms pursuing virtual strategies, such as NEC, Toshiba, Western Digital and Maxtor, had no such dynamic flexibility, their ability to incorporate MR technology in its integral phase state was severely curtailed.

Conclusion

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

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

Firms that do not so align themselves are at risk of falling into one of two organizational traps. One is an integrality trap, in which a centralized firm continues to rely on managerial coordination in a modular phase of technology to manage its technology development. The other trap is a modularity trap, in which firms that achieved success by means of decentralized coordination via the market continue 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 to incorporate MR technology, effectively ignoring the importance 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 outside 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 designing disk drives. Firms such as IBM and Fujitsu, which possessed the technical ability at the systems and component levels and employed a centralized organizational strategy to manage the technology transition of disk drive heads to 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 speedy and agile This is certainly true in some industries where technology is in a modular phase. If technology is integral, as it is in the automobile industry, integrated organizational strategies work better to produce profit from innovation opportunities. Similarly, industries in which the technology is stably modular may benefit more from delayed, horizontally organized, more virtual approaches.

While this contingent perspective is common among academic scholars 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

1 We adopt the term 'integral' to highlight the organizational implications of this type of technology and 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 Our account of the introduction of thin film heads in this section draws heavily from Christensen's extensive research programme in hard disk drives. See Christensen, 1992, 1993 and 1997 and Christensen and Chesbrough, 1999.

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PART III
MANAGING KNOWLEDGE AND TRANSFORMATION

11 Can Knowledge Management Deliver Bottom-line Results?

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Introduction

In late 1996, NatWest Markets – the investment banking arm of Britain's NatWest Group – appointed the well-regarded banker Victoria Ward as its first Chief Knowledge Officer (CKO). Her goal? To improve the productivity of 7,000 employees around the world by giving them access to each other's knowledge – ideas, lessons learned, specific client understandings, the locations of experts and so on. Recognizing that the driven and accomplished investment bankers would resist being told by a CKO what knowledge mattered most, Ward enlisted champions from various business unit line organizations who shared her conviction that by enabling sharing among investment bankers, productivity would improve. Ward and her small team of seven worked with these champions to rapidly launch a series of sharing and collaboration pilots. However, the investment bank, unconvinced of the value of these pilots, ended its foray into knowledge management less than a year after appointing Ward as CKO. Frustrated, but convinced of the power of knowledge management, Ward left and started her own knowledge management consulting business.

According to John Browne, CEO of British Petroleum, 'to generate extraordinary value for shareholders, a company has to learn better than its competitors and apply that knowledge through its businesses faster and more widely than they do' (Prokesch, 1997). BP has outperformed competitors in recent years – in part by continually launching initiatives to leverage the knowledge of customers, contractors, vendors and employees.