Dynamics of innovation in the semi-conductor industry

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Background

There is much to say about the semiconductor industry. This analysis is not aimed at explaining why it exists or how it came to be what it is today. Its main intention is to provide some insight into the organizational structures, types of knowledge, design principles and underlying sources that drive innovation within the industry.

The semiconductor industry, like most industries, relies on selling products to consumers for a profit. This is not an easy task, as it involves collecting information from users regarding their needs and preferences, developing a product with existing organizational capabilities, incrementally improving the product to achieve market fit, developing internal processes to increase product quality and/or reduce costs, and avoiding disruption from potential competitors. We shall follow this familiar path to analyze some of the previously described phenomena present in this industry.

Gathering user needs

To develop a product, it is essential to obtain information about user needs. However, as research by Von Hippel and others has shown, there are cases where acquiring this information has a cost. This type of information is referred to by Von Hippel as “sticky information”. Information can be “sticky” for a few reasons. First, information can be hard to transfer due to its tacit nature. Technical knowledge can be “indefinable”, such as a set of practices, and thus hard to communicate. Second, the amount of information might be too big to easily transfer. And last, information can be sticky because the recipient of the information must have sufficient skills and knowledge to be able to use the information that is transferred to them. When the cost of transferring information is high, innovation and problem solving must happen at the place of origin of the information. This is one of the reasons why problem solving is frequently carried out by product users who possess information obtained by interacting with the product. (von Hippel, 1994) Firms that are better able to overcome the challenges of sticky information regarding user needs are usually more likely to succeed.

Paradoxically, there are cases when listening to customers and gathering information can lead to failure. This can happen when "good" companies blindly follow the recommendations of their main customers and end up ignoring emerging markets. This is what Christensen calls the "innovator's dilemma". One example in the semiconductor industry is the development of 8-inch disk-drives. Initially, these drives offered lower storage capacity and came at a higher price compared to 14-inch drives. This made them undesirable to the main customers of industry incumbents - mainframe computer manufacturers. However, they proved especially attractive to mini-computer manufacturers who were willing to pay more for smaller sized disks. Since mainframe computer manufacturers were only interested in disks being cheaper and having greater capacity, incumbents ignored the 8-inch drive market. Eventually, the 8-inch drive makers innovated and increased the capacity of their drives. This enabled them to capture the mainframe market and drive out the established manufacturers of 14-inch drives. (Christensen, 1997)

Beyond user needs, there are other areas where information is also sticky. One example is the process of designing a silicon integrated circuit on a semiconductor chip for a custom application. Not only are user specifications sticky information due to their complex nature, but also the knowledge about constraints and possibilities of the silicon fabrication process that the manufacturer uses to produce the integrated circuits. As Von Hippel points out, the dual location of the sticky information gives rise to an iterative process where the problem-solving activity shifts back and forth between the two sites. In this case, a prototype is sent out to the user for testing and sent back for redesign until it meets user requirements. Since this process can be costly, efforts are made to “unstick the information”. In this case, the Application Specific Integrated Circuit (ASIC) method of making custom integrated circuits was developed. Through this method, consumers can make use of dedicated software that enables them to design their custom interconnection layer without falling out of the manufacturer’s capabilities. This way, the problem-solving activity was successfully shifted to the locus of sticky information regarding the user’s unique application. (von Hippel, 1994)

Product development and production

According to Utterback, product development goes through a set of phases before coalescing into a dominant design. In the beginning, in what he calls the “fluid phase”, the rate of product innovation is very high and there is not much attention directed towards increasing performance. In the next phase, the “transitional phase”, the rate of product innovation slows down and focus shifts to process innovation. This is where the transition from product variety to a standard design happens. Finally, there is the “specific phase”, where innovation is very limited in both product and process. (Utterback, 1994)

One good example is the rise of EUV lithography. Lithography is a technique used in the semiconductor industry to create circuitry patterns in silicon wafers by using light-sensitive chemicals. To meet customer demands, circuits continuously shrunk until the industry had to adopt special light sources to create nanometric patterns. At least four different technologies emerged to tackle this challenge. In the end, EUV technology had superior throughput and reliability, so it became the dominant design. It then entered a period of process refinement until it was ready for high-volume manufacturing. Today, this technology is used to produce the ultrafine circuitry necessary for the most advanced semiconductors. (VerWey, 2024)

By pairing the phases of product development with Von Hippel's sticky information and Allen's findings showing how important distance and organizational bonds are in the amount of information that is exchanged inside a workplace (Allen, 1977), we can now dive into the theory behind Vernon's product cycle and its locational implications in design and production.

As we saw, in the early stages of production, product development is in the "fluid phase", the period when the product specification is highly unstandardized. (Utterback, 1994) During this phase, producers value the degree of freedom with which they can change their inputs. In addition, the elasticity of demand in the early stages of a product is relatively low, meaning that potential customers should be willing to pay more for a highly differentiated product which might also be a monopoly. Lastly, producers need to be able to communicate effectively with consumers.

Since the above factors are crucial in early product development, it follows that producers will locate in places where they can meet these requirements. The United States is one of such places for two reasons. First, the United States' market consists of consumers with a higher average income. Second, it is characterized by high labor costs and easy access to capital. This means that there are innumerable opportunities for innovations that address the need to conserve labor, and producers are more likely to be aware of the possibility of introducing new products. This is consistent with the appearance of innumerable inventions in the United States, including the sewing machine, typewriter and tractor. (Vernon, 1966)

During Utterback's transitional phase, the product matures and the need for flexibility declines. New standards are set in place. The focus shifts towards reducing costs and increasing product quality. Producers might start moving production towards cheaper locations within the United States and might be willing to set up production in other countries if labor costs offset the transport costs associated with producing everything at a central location in the United States. Finally, as the product reaches its final stages of development, the whole focus is to ensure quality and to reduce costs. In this phase, production is moved to the low-wage south. Factors that were relevant before, like access to information, have been resolved. (Vernon, 1966)

This explanation provides some insight into why the United States has been losing semiconductor manufacturing capabilities for decades. (Singh, Sargent, & Sutter, 2023) However, the semiconductor industry is one of the most complex. Five thousand suppliers providing 100,000 parts, 3,000 cables, 40,000 bolts and two kilometers of hosing are needed just to make an EUV tool. (VerWey, 2024) This complexity makes it hard to transfer information, which means it is highly sticky. One common approach for reducing the costs of information transfer is to partition tasks into subproblems so that they only need to draw information from one source. (von Hippel, 1994) However, for the pieces to work together, a need for a coordinating system arises. This is often achieved through "modularity in design". With this method, different parts are designed independently and then interconnected seamlessly due to their adherence to a predetermined set of design rules. Modular architecture can create huge value by providing options for designers and allowing innovation to occur within a module without affecting the overall system. It allows complementary products to have a positive externality in the whole system, unlocks value by utilizing interfaces that minimize costs associated with both switching costs and information transfer, as new suppliers can seamlessly integrate. (Baldwin & Clark, 2000)

Avoiding disruption

To compete in the market, achieve differentiation and gain market share, firms recur to innovation. According to Abernathy and Clark, there are four types of innovation. Architectural innovation, which centers on the creation of new technologies that break away from traditional production methods to address new markets, niche innovation, which involves using existing technology to address new markets by meeting customer needs through improved designs and technical versatility, regular innovation, which is the usual way in which existing skills and resources are used to perfect the product in order to meet a wider range of user demands, and finally revolutionary innovation, which applies to existing markets and renders existing technical and productive capabilities obsolete. (Abernathy & Clark, 1984)

On the other hand, Christensen argues that innovation occurs in two types of technologies: sustaining technologies, which are technologies that improve the performance of established products, and disruptive technologies, which relate to innovations that offer new features to a new set of customers, are typically simpler, cheaper or more convenient to use but may initially have a worse performance than established products. This is the case with the 8-inch disk drive example we described earlier. (Christensen, 1997)

Based on both explanations, one could conclude that avoiding disruption just means keeping an eye out for new markets (Christensen) or new technologies (Abernathy and Clark). This is easier said than done, especially in industries where powerful constraints limit their ability to change directions. An important aspect of a dominant design is that it is the result of a “technological trajectory". This means that previous decisions about the product constrain the nature of the dominant design. (Utterback, 1994) This concept resonates with North's increasing returns and path dependence. (North, 1990) This characteristic is also present in modular architecture, because once released into the market, links between components become difficult to adjust and "take a life of their own". This means that, sooner or later, the dependencies between components will compromise the industry's capacity to advance leading to what Chesbrough calls a "modularity trap". Indeed, there seems to be a lack of systems level innovation in the consumer electronics segment when compared to the personal computer market. (Chesborough & Kusunoki, 2001) The modularity trap makes incumbent firms vulnerable to disruption, as their system-level capabilities are impaired.

One very clear example is the case of Intel, the producer of microprocessors. Their product is, for the most part, only relevant when used in conjunction with another product, such as a computer. In the mid-2000s they invented the 64-bit microprocessor but were unable to gain any benefit from it unless software companies like Microsoft and Oracle redesigned their products to fit the innovation. (Gawer & Cusumano, 2002)

To address the challenges of modularity, Gawer and Cusumano developed a framework to help guide a strategy towards platform leadership. It provided four levers that could be used to influence the modular ecosystem. First, the scope of the firm, deals with the question of what tasks will be done internally by the firm, or externally by complementors. Second, product technology, is concerned with architectural decisions such as the level of modularity and the degree of openness of the interfaces to the platform. Third, relationships with external complementors, deals with the question of whether the firm should adopt a collaborative or competitive approach toward complementors or platform leaders. Fourth and last, the internal organization structure designed to handle conflicts of interest more effectively. As Gawer and Cusumano explained, Intel used these levers to break out of the modularity trap and lead the initiative to create a new peripheral component interconnect (PCI). A risky bet that expanded the scope of Intel's work beyond its traditional work in microprocessors but enabled the industry to move forward. (Gawer & Cusumano, 2002)

Conclusion and future lines

This paper provided some brief insights into the dynamics driving innovation in the semiconductor industry. It described the process for gathering valuable user information and making use of it in the most efficient manner during product design. It talked about some of the forces that shape product design and constraints that prevent future improvements. It briefly analyzed why some companies fail and how to prevent disruption stemming from the emergence of new markets or technologies.

In the future, more specific and thorough analysis can be made regarding the overall semiconductor industry and innovations in semiconductor manufacturing equipment, which is a topic that I am researching. This analysis did not touch the subject of networks of innovators and the characteristics of research in the semiconductor industry. Future work can be done in that direction.

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