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Who captures value from science-based innovation? The distribution of benefits from GMR in the hard disk drive industry

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ABSTRACT

We analyze the discovery of giant magneto-resistance (GMR) and its development and commercialization by the global disk drive industry to answer the question of "Who captures the benefits from innovation in a global innovation system?" We assess the returns to the scientists, firms, and countries associated with GMR. We find that the French and German scientists that discovered GMR and their labs benefited by receiving the Nobel Prize and small licensing fees. The firm that first commercialized the technology, IBM, captured profits from selling hard disk drives and magnetic heads using GMR. Other hard disk drive and head manufacturers based in the U.S. and Japan were able to quickly assimilate the technology and catch up with IBM. France and Germany reaped limited returns due to the lack of domestic firms with the absorptive capacity to commercialize GMR. The U.S. and Japan benefited from the success of their firms in commercializing GMR, as did other countries which were part of the global value chains of those companies. Consumers and firms that incorporated hard drives in their products ultimately benefited from cheaper hard drives with greater capacity. These findings illustrate the importance of absorptive capacity at the firm and national level in capturing benefits from innovation. They also show that the benefits to first mover firms can be short-lived in a competitive industry with open transfer of knowledge and limited appropriability regimes. Finally, they show that the location of jobs and wages associated with innovative products depends on the structure of the global value chains of leading firms.

1. Introduction

There has been a great deal of research attempting to quantify the benefits of R&D in fields such as economics, public policy and management (Nelson, 1959; Arrow, 1962; Rosenberg, 1982; Teece, 1986; Dasgupta and David, 1994; Mansfield, 1996; Dosi et al., 2006). Yet, questions remain about the relationship of R&D to economic performance. Although there is evidence of economic benefits from R&D at the firm and country level (Griliches, 1992; Jones and Williams, 1998), the level of contribution has been questioned (Comin, 2004), and causality is not always clear (Hall and Kramarz, 1998). The relationship is even more tenuous in the case of basic research, which may or may not have any commercial application.

Even when basic research leads to commercially successful innovations, there is still a question about who benefits from this success. In a global economy, countries that invest in basic research may see the outputs of that research commercialized in other countries that do not contribute to the research effort (Pavitt, 2001). In the words of Mansfield (1996: 136):

> "The contribution of research to a nation's economic performance depends on how well the nation's firms can utilize and commercialize research to bring about profitable new products and processes."

This issue has been a concern of the European Union since the 1990s. As put by the European Commission (1995) in its Green Paper on Innovation:

> ". . . Europe suffers from a paradox. Compared with the scientific performance of its principal competitors, that of the EU is excellent, but over the last fifteen years its technological and commercial performance in high-technology sectors such as electronics and information technologies has deteriorated."

In this paper, we look at a case of a very successful European scientific effort, the discovery of giant magneto-resistance (GMR), which had significant commercial value in the hard disk drive

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(HDD) industry. The GMR principle was discovered independently in the late 1980s by physicists Albert Fert of France and Peter Grunberg of Germany, who shared the Nobel Prize in 2007 for their discovery. This research enabled manufacturers to make significant improvements in the "heads" which read data from spinning disks in HDDs, and along with previous and concurrent innovations, paved the way for smaller drives with dramatically greater capacity.

The company that first commercialized GMR in 1997 was IBM, which transformed GMR from a scientific principle into a working product. Other firms followed IBM quickly in adopting GMR. After a round of acquisitions, including IBM's sale of its HDD business to Hitachi, the U.S. HDD industry consisted of Seagate and Western Digital, both of which made most of their own heads. Japan was left with four HDD makers and two independent head manufacturers. European firms were unable to translate GMR into commercial products, even though several tried.

Why were no European companies able to participate in the success of GMR, even though Europe was home to large electronics manufacturers? How was IBM able to successfully commercialize GMR technology but unable to achieve a sustainable competitive advantage? Who captured the greatest value from GMR and why? What lessons does the GMR case teach us about the ability of firms and countries to capture value from science-driven innovation?

To explore these questions, we present an in-depth case study of GMR from its scientific discovery through the process of technological development and commercialization (1985–2006). In Section 2, we frame our analysis in the theory of absorptive capacity. Section 3 describes the global value chains in the HDD industry. Section 4 presents the facts of the GMR case from discovery to development, to commercialization and imitation. Section 5 presents our methodology for estimating value capture by firms in the industry and economic benefits to countries. Section 6 presents the distribution of benefits for scientists, firms and countries. Section 7 discusses why some firms were able to benefit from the discovery whereas others were not, in terms of absorptive capacity theory. Section 8 discusses the implications for theory and Section 9 discusses the policy implications.

2. Conceptual framing: absorptive capacity

The concept of absorptive capacity has been used to understand how firms and countries are able to recognize the value of, assimilate, and commercialize new knowledge (Cohen and Levinthal, 1990). It is based on the idea that exploiting external knowledge is not easy or costless, but requires effort and capabilities on the part of recipient firms or countries. Absorptive capacity consists of an array of learning and problem-solving skills needed to address the tacit components of external knowledge, make modifications, and create new value (Mowery and Oxley, 1995; Kim, 1998). These capabilities exist within both firms and countries.

2.1. Determinants of absorptive capacity

A key question is what factors determine the absorptive capacity of firms and countries. At the firm level, Cohen and Levinthal (1990) argue that absorptive capacity for new knowledge depends on a firm's *existing related knowledge*, and that "prior knowledge permits the assimilation and exploitation of new knowledge" (p. 136–137). This prior knowledge can be the result of a firm's R&D investment as well as its manufacturing experience, managerial techniques or market knowledge (Easterby-Smith et al., 2008). Cohen and Levinthal (1990) also argue that absorptive capacity is firm-specific and new knowledge cannot easily be bought and integrated into a firm, for instance through hiring, licensing, or acquisition of other firms with desired knowledge. Instead it requires long-term investment in R&D to accumulate absorptive capacity.

Several *knowledge characteristics* have been identified as influencing the ease with which it can be absorbed by a firm. Tacit knowledge is more difficult to absorb than explicit or codified knowledge (Kogut & Zander, 1993), especially when it is embedded in a firm's unique processes. Complex knowledge that touches more people, technologies and processes is more difficult to absorb (Lane and Lubatkin, 1998), as receiving firms need a wider range of related knowledge to assimilate and exploit the new knowledge.

Studies of the hard disk drive industry, (e.g., Christensen and Rosenbloom, 1995; Chesbrough, 2003) find that new generations of smaller, cheaper drives caught established companies off guard and led to the rise of start-ups such as Seagate, Maxtor, Quantum and Conner Peripherals to supply HDDs for the PC industry. Yet IBM survived as a market leader, along with established Japanese firms such as Fujitsu, Hitachi and Toshiba. It is important to sort out exactly what knowledge firms have accumulated and whether new knowledge enhances or destroys the value of the accumulated knowledge. In this case study, we address this issue as it relates to adoption of GMR.

Industry environment has been posited to play a role in absorptive capacity. As knowledge becomes more complex and changes rapidly, it is difficult for a firm to keep up with and exploit all relevant knowledge (Lane and Lubatkin, 1998). Firms need to work with suppliers, partners and customers to keep up, or they may hire people from competitors or acquire suppliers or competitors outright. Such collaboration can benefit the entire industry by increasing demand for its products and fending off competition from substitutes (e.g., other forms of information storage). At the country level, the presence of an industry cluster that includes lead firms (Sturgeon, 2002) and suppliers, customers and providers of complementary technologies is a source of absorptive capacity. Silicon Valley is the leading example in electronics, followed by secondary clusters such as Korea, Taiwan, and Southeast Asia. These geographic clusters within or across countries are posited to have greater absorptive capacity than individual firms (Giuliani, 2005).

2.2. Absorptive capacity and capturing value from knowledge

It is argued that absorptive capacity enables firms and countries to create and capture value from external knowledge. For firms, it can result in competitive advantage and greater profits. For countries, it can support economic growth and job creation. Yet there is little empirical evidence of the impacts of a particular innovation such as GMR. An important question is how much value is captured by firms and countries from the assimilation and commercialization of new knowledge, and what factors determine the distribution of value capture.

For firms, the answer to this question depends on whether absorptive capacity can be a source of competitive advantage and superior performance (Zahra and George, 2002). It is argued that absorptive capacity can be a form of dynamic capability (Teece et al., 1997; Zahra and George, 2002) that enables firms to respond effectively to change in turbulent conditions. The concept of absorptive capacity has been applied to examine firm innovation performance in a variety of industries, such as electronics, pharmaceuticals and biotechnology (Lim, 2004; Arora and Gambardella, 1994). Absorptive capacity has been found to be a source of competitive advantage, enabling firms to manage external knowledge to achieve higher firm performance (Escribano et al., 2009).

One factor determining the ability of firms to capture value from new knowledge is the *appropriability regimes* that exist in an industry. This term was defined by Teece (1986:287) as "the environmental factors, excluding firm and market structure, that govern an innovator's ability to capture profits generated by an innovation.

In the absorptive capacity literature, appropriability is looked at in two ways—as a determinant of (1) firm investment in absorptive capacity and (2) value capture from innovation. When appropriability in an industry is low, knowledge flows easily across firm boundaries, giving firms an incentive to maintain the capabilities to acquire this knowledge. On the other hand, low appropriability limits value capture, and ultimately firms' incentive to invest in absorptive capacity will be lower. Which of these effects is stronger is treated as an empirical question (Cohen and Levinthal, 1990). But if firms cannot appropriate value from investments in innovation, they may abandon an industry, be acquired, or go out of business until the market becomes more stable and remaining firms gain enough scale and pricing power to sustain profitability.

It has been argued that over time, the absorptive capacity of firms will converge across an industry, especially as an industry matures, making it harder to sustain competitive advantage (Eisenhardt and Martin, 2000). However, others have argued that firms that continue to invest in absorptive capacity can sustain competitive advantage and earn higher profits by being able to identify and respond to changes in the technical and competitive environment (Zott et al., 2000; Cockburn et al., 2000). As we will see in the case of HDDs, absorptive capacity did converge among the leading firms.

The concept of absorptive capacity also has been used at the level of countries (Castellacci and Natera, 2012) and regions or geographic clusters (Giuliani, 2005). In the case of countries, successful innovation is considered a key to sustained economic growth, job creation and improved living standards (Castellaci and Natera, 2012). Success depends partly on the presence of people and institutions that enable creation, acquisition and exploitation of internal and external knowledge (Nelson and Rosenberg, 1993). These institutions include national research labs, private firms, universities, government agencies, labor markets, and financial markets (Chesbrough, 1999).

Appropriability regimes in the same industry can vary greatly across countries. For instance, patent protection in the U.S. and Europe gives pharmaceutical companies a temporary monopoly on innovative drugs while they are under patent. But in other countries, they face strong price competition from local generic producers even while under patent (Schacht and Thomas, 2005). Some countries favor domestic manufacturers in government procurement. Some countries have relatively high or low labor mobility and the ease of making acquisitions varies across countries.

The success of countries in capturing value from science and innovation also depends on the presence of globally competitive firms that can reap economies of scale, maintain strong profit margins, sustain R&D efforts, protect intellectual property and provide high quality jobs. In most cases this means domestically-based firms (Linden et al., 2009), but some countries have been able to attract foreign multinationals to do R&D, process engineering or other knowledge-based activities that benefit local economies (Ernst et al., 1998).

The literature on absorptive capacity (Appendix A, Table A1) mostly consists of conceptual papers (e.g., Cohen and Levinthal, 1990; Zahra and George, 2002) and quantitative studies (e.g., Cohen and Levinthal, 1990; Boynton et al., 1994; Matusik and Heeley, 2005) at the firm level. In addition, there are conceptual (Mowery & Oxley, 1995) and quantitative (Castellacci and Natera, 2012) country level studies. These build and test models of absorptive capacity, its antecedents, and its outcomes, but do not look in depth at the actual process and context in which new knowledge is assimilated and applied.

There is a need for case studies that look at a specific technology throughout the stages of discovery, assimilation, and commercialization. There also is a need to study who captures value in such an innovation when these stages are spread across multiple individuals, firms and countries. Finally, there is a need to make the connection between the success of firms and countries in the creation and deployment of new knowledge.

This case study focuses on critical details of GMR, including its relationship to precursor technologies, the position of GMR heads as one of many critical components in a hard disk drive, and the coevolution of GMR heads with those other components that enabled dramatic gains in storage capacity in ever smaller drives. It also focuses on the nature of the HDD industry and the firms and people in the industry. It shows how the Nobel Prize-winning discovery of GMR was transformed into a commercial innovation by one company, and how that knowledge spread quickly to the rest of the industry. Finally, it estimates the economic value created by this innovation, and which firms and countries were able to capture that value.

These findings build on and extend existing knowledge of absorptive capacity at the firm and country levels. The unique contributions of the case are a deeper understanding of how the nature of a technology, its relationship to other technologies, and the industry context and market environment in which it is assimilated, transformed and exploited, influence the outcomes for firms and countries.

3. The hard disk drive value chain

The HDD is a highly complex product with four key physical components: head subassemblies, media, motors and electronics. The read/write heads, which are the focus of this study, are the most costly component and "have an enormous impact on drive design and performance" (McKendrick et al., 2000; p. 22).

The manufacturing process begins with semiconductor-like wafer fabrication. The wafers are machined into sliders, which are the tiny read/write elements. The sliders are attached to a suspension, which is a small arm that holds the head in position above or beneath the disk. This process is called head gimbal assembly (HGA) and is very labor intensive. Sets of HGAs assembled together for installation in a disk drive are called a head stack assembly (HSA). A typical hard drive has 3-4HGAs. While our measurements are based on HGAs, we will use the word "heads" in place of HGA throughout the paper for simplicity. Fig. 1 shows the activities involved in hard drive manufacturing with the grey area indicating the focus of this study.

Early magnetic heads in disk drives were based on the principle of induction to read and write data on magnetic disks. The inductive process was used to create strong magnetic fields to write on the hard magnetic material on the surface of the recording disk. The reverse of this inductive process was used to read back the information. Using a single element for both reading and writing increased the inherent conflict between the two functions as areal densities increased (Bajorek, 2014).

HQ/ R&D/ S&M	Head mfg.	Head gimbal assembly	Head stack assembly	Disks Mfg.	Motor Mfg.	PCBA Mfg.	Enclosure Mfg.	HDD assembly	Logistics/ warranty/ tech support

Fig. 1. Activities in hard drive design and manufacturing.

Magnetoresistive (MR) technology introduced separate elements for each function—an inductive write head combined with a magneto-restive element to provide the read function. It allowed each function to be optimized for its purpose and greatly increased the reading efficiency of the head. GMR technology is an advanced application of MR technology and provides significantly stronger signals than its predecessor anisotropic magnetoresistance (AMR) recording heads, thereby enabling higher areal densities. GMR heads employ multiple layers of ultra-thin films of conducting metals that enable the heads to be much smaller as well as much more efficient.[1] This, in turn, enabled the design of much smaller hard drives with larger capacity. AMR heads were introduced by IBM in 1990, followed by GMR, also introduced by IBM in 1997.

Other component innovations paralleled the development of MR heads, most importantly thin-film disks that store data and are read by the heads. In addition, important manufacturing processes were developed to make commercial production possible. Head manufacturing is highly capital intensive and employs a small number of engineers and highly skilled technicians. It is done in clean rooms and usually located in the home country of the manufacturer where R&D and development are also located. By contrast, the head stack assembly (HSA) process is labor intensive and done mainly in Southeast Asia, where the industry's manufacturing base and supply chain had been established in the 1980s. There also is manufacturing by Seagate in Northern Ireland. During the time period of this study, HGA manufacturing was split between vertically integrated firms (IBM, Seagate, Hitachi) and independent suppliers (Alps Electric, TDK/SAE Magnetics and Read-Rite). In 2003, Read-Rite was acquired by Western Digital and IBM's drive business including head manufacturing was acquired by Hitachi.

4. Discovery, development and commercialization of GMR

Next we describe the role played by participants in each innovation phase related to GMR: (1) the academic scientists in discovery, (2) the industry scientists and engineers in product development and (3) the companies in commercialization.

4.1. The scientists and discovery

The Nobel Prize in Physics was awarded to Albert Fert and Peter Grunberg in 2007 for experiments they conducted in the early- to mid-eighties that were the "origin of the discovery of giant magnetoresistance" (http://www.nobelprize.org/nobel_prizes/physics/laureates/2007/. Last accessed 1/23/15). Albert Fert was an academic scientist from the University of Paris who conducted experiments working with equipment and an engineer from Thomson CSF, an electronics and defense contractor (Fert, 2009). Peter Grunberg was a government scientist at the Jurlich Institute for Physics (focused on atomic physics) whose staff assistant built a machine for the experiments (Schneider, 2010). The GMR discovery was reported at the June 1988 International Conference on Magnetic Films and Surfaces (ICMFS) Le Creusot, France. Grunberg recalled:

> "...both of us gave a talk [at ICMFS] and after the talk we stated 'Yes, we obviously found the same kind of an effect.' We found it in double-layer structure, with two magnetic films, and Albert had a multi-layer structure, and therefore it was stronger in his case, but we realized that it is the same kind of physics which leads to this effect in the two different systems" (http://nobelprize.org/nobel_prizes/physics/laureates/2007/grunberg-telephone.html. Last accessed 1/23/15).

The experiments proved the theory, but neither Grunberg nor Fert moved to the next phases of development and commercialization. The two scientists were only interested in the scientific aspect, although Grunberg recognized the commercial potential, saying in his Nobel Prize lecture that "At the time of the discovery of GMR, it was well known that leading computer companies planned to develop AMR so it could be used for read heads in hard disk drives. The comparison between AMR and the effect encouraged us to file a patent for using GMR in HDD" (Grunberg, 2007). The Jurlich Institute, which had staff and experience in patenting, filed the patent (Schneider, 2010). Fert indicated that neither he nor the University had experience or staff for patenting; Thomson filed, but was too late as Jurlich was first (Fert, 2009).

4.2. Industry R&D and product development

Stuart Parkin, a scientist at IBM, was instrumental in moving GMR from discovery to product development. Parkin was Cambridge-educated with a PhD from the Cavendish Laboratory and joined IBM Research in 1982. He was at the 1988 conference where Fert and Grunberg announced their discoveries and said that at first GMR did not look very interesting from a commercialization perspective because it would be very hard to convert to application.[2] However, the potential to increase storage capacity while also enabling a decrease in the size of drives was so great that he went to work on it (Parkin, 2010).

Moving from the basic discovery not only required technology research, but it also required fundamental research in physics (Parkin, 2010; Schneider, 2010; Mills, 2010). The GMR discovery had occurred using the MBE (Molecular Beam Epitaxy) method and very large magnetic fields under very low temperatures. To be useful in a commercial product, it was necessary to use small magnetic fields at room temperatures and to research a variety of materials to discover which had the best characteristics for application.[3]

Fert had argued that the GMR effect was a very special property of chromium and iron, and that the effect was due to the internal structure of these materials. Parkin theorized that the effect might be found with other materials and that the effect might be due to the interlayer coupling of materials rather than the structure of the materials themselves. He was able to reproduce the GMR effect with iron and chromium and also with a host of other materials (silver, copper, gold, cobalt, ruthenium and nickel oxide). More importantly, he showed that the effect increased monotonically up to some level of thickness of the metal used and then saturated, whereas Fert had predicted that it would decrease monotonically with thickness. Finally, he showed that he could produce GMR with just two magnetic layers separated by a spacer layer in small magnetic fields—what he called a spin valve (Parkin, 2010).

[1] McKendrick et al. (2000) pointed out that a thin-film head was only 1/25 as big as the earlier ferrite heads and that MR heads allowed a 30% increase in the number of tracks on a disk and about 15% more bits within each track.

[2] Mark Kryder of Seagate was also present at the conference, and said neither he nor others came back to their lab to work on it because "It was pretty hard to expect that there was going to be a product from the discovery." He gives credit to Parkin for "...seeing the possibility and trying to understand the mechanism at work. He found out how to produce the GMR effect at room temperatures with very small magnets. Once it was understood, everybody saw the potential and got into GMR" (Kryder, 2010).

[3] Creating samples with which to study the GMR effect involved a very exotic, expensive method using Molecular Beam Epitaxy (a million dollar machine). It also involved very large magnetic fields of 2 tesla, which is 20 thousand times too big to be useful in application. And the effect could only be generated at very low temperatures (Parkin, 2010).

4.3. Companies and commercialization

4.3.1. IBM

IBM was the first company to bring out heads based on GMR and it took nearly ten years from the Fert/Grunberg discovery to delivery of HDD product in the market. By way of comparison, IBM had started work on MR heads in 1969, and had a working prototype by 1983, and finally a product by 1990 (Bajorek, 2009), showing the sustained effort in R&D required for these innovations. By 1991, Parkin had developed very small, multilayered sandwiches of materials called "spin valves" that met the need for the very small magnetic fields required in the head of an HDD (Parkin, 2010). It was then the job of IBM Research's Disk Storage Research Unit to develop a physical sensor that could be incorporated into a hard drive.[4] In 1994, IBM Research announced it had created the world's most sensitive head for detecting computer data on magnetic hard disks using the GMR effect. Next, IBM's Storage Division in San Jose had to integrate the head into a new drive, to build physical prototypes that could be tested rigorously and to ramp-up production for full-scale manufacturing.

In December 1997, IBM announced a 16.8 GB 3.5-inch HDD product using GMR heads for the desktop market and claimed a major improvement in aerial density over previous drives.[5] In early 1998 IBM began production of a 6.48 GB 2.5-inch HDD for the mobile computer market (www.hitachigst.com/hdd/technolo/gmr/gmr.htm. Last accessed 1/26/2015). Because these GMR heads contained both read and write capabilities, they also had fewer components which translated to lower manufacturing costs, higher reliability, and lower power requirements.

4.3.2. Other U.S. companies

In 1999, there were only two other U.S. companies making heads besides IBM—Seagate, which was a vertically integrated disk drive maker, and Read-Rite, which was a merchant producer. Competition from Japanese merchant producers, and the loss of some contracts (from failing HDD customers), caused Read-Rite huge losses in the early 2000s and it was bought by one-time customer Western Digital in 2003. When IBM sold its HDD business in 2002 to Hitachi, Seagate was the leading U.S. maker of GMR heads. Western Digital had just started making its own GMR heads.

Historically, the mobility of engineers and ready availability of venture capital had led to creation of new startup companies in the U.S. making HDDs (Christensen, 1993; Chesbrough, 1999). Often, former IBM engineers headed these companies so they had considerable knowledge and experience about how to develop and manufacture quality products and bring new innovations to market quickly. Estimates vary, but there were about 50 HDD startups in the U.S. over 30 years (Christensen, 1993; Chesbrough, 1999). After a round of acquisitions, Seagate and Western Digital were the principal U.S. HDD suppliers to IBM and the other PC makers (Dell, HP, Compaq, Gateway, etc.) and thus survived the brutal international price competition in the HDD industry. In 1999, there had been five leading U.S. hard drive firms (IBM, Maxtor, Seagate, Western Digital, Quantum), mostly losing money, but after a series of acquisitions, there were only two: Seagate and Western Digital accounted for 63.6% of the global HDD market at the end of 2006.

4.3.3. Japanese companies

In contrast to the small number of U.S. head makers, there were seven Japanese firms making heads: TDK/SAE Magnetics, Alps Electric, Yamaha, MKE Peripherals, Yamaha, Hitachi, Ltd. and Hitachi Metals. All were part of large Japanese conglomerates with internal markets as well as external ones. Fujitsu and Hitachi made heads for their own use, but they and the other head makers also were OEM producers selling to Japanese, European and U.S companies. Unlike the U.S., where heads and HDD makers relied mainly on the computer industry, the Japanese makers also supplied the vast consumer electronics industry centered in Japan and Asia. Initially, the Japanese firms were about three years behind IBM's head technology, but they caught up by 2003 through licensing technologies from IBM and through their own R&D investments. The leading head maker, TKD/SAE, had acquired a company called Headway, which had been started by a group of former IBMers and acquired GMR technology from Hewlett-Packard, which had its own GMR program (Bajorek, 2014). As summed up by McKendrick et al. (2000, p. 84), the Japanese "have not been far behind their U.S. competitors on the technological frontier and even introduced advanced new products before leading U.S. companies did." A notable example was Toshiba, whose 1.25 inch HDD was used in the early iPod models.

5. Methodology for measuring value capture

In order to assess who captured what value from GMR, we examine the financial and other benefits realized by the key participants in this innovation: (1) the scientists who discovered GMR, (2) the companies and their R&D labs that developed a workable product, (3) the HDD companies who commercialized the technology, and (4) the countries of the scientists and engineers, research institutions and firms—France, Germany, Japan and the United States (Table 1).

We use multiple methods and measures to assess value capture from the GMR discovery and commercialization by individuals,

Table 1
Participants/potential beneficiaries in GMR technology.

Innovation Phase	Participants	Role
Discovery	Albert Fert (France) Peter Grunberg (Germany)	GMR discovery
Development	Stuart Parkin, IBM Almaden Research Center, IBM Storage Division, United States.	R&D & engineering for manufacturability
Commercialization	US: IBM Storage Division, Seagate, Read-Rite, Western Digital (after the acquisition of Read-Rite) Japan: MKE, Alps Electric, TDK/SAE Magnetics, Hutchinson, Fujitsu, Hitachi, Toshiba	Manufacturing of heads

[4] IBM's expertise and previous experience with thin films helped as IBM had pioneered AMR heads for disk drives with the introduction in 1991 of a 1 Gigabyte (GB), 3.5-inch drive, which provided the highest areal density available at the time. It reached 3 Gigabits per square inch by 1997 and was nearing the end of possibilities for further improvement from AMR heads.

[5] There are differing opinions about the relative significance of GMR and Parkin's contribution, but all agree that GMR was significant, as was Parkin's contribution. Chris Bajorek, formerly of IBM, argues that AMR technology was a more significant innovation than GMR, which was just a step along a technology trajectory. Bajorek says: "The portrayal of the significance of GMR is exaggerated by many in the industry and also by the Nobel Committee. GMR did not increase the capability of HDDs 1000 fold as an IBM announcement inadvertently implied. There are hundreds of elements in a HDD that have to synch for it to work. Everyone thinks his part is the key. The head is only one part of a HDD and the read element of the head (where the GMR effect was used) is only a subset of the head. GMR improved things by orders of magnitude, but not 1000-fold. Two significant inventions were film disks and MR. The industry invented film disks in the early 80s and had products by 1983. By 1987, 100% of the industry had converted to thin film. The film disk is more critical to HDD than the head. I would ascribe improvements to HDDs as follows: 60% to the film disk, 15–20% to heads [where the GMR effect was used], and 15–20% to fly height, electrical circuitry, data detection methods and other elements" (Bajorek, 2009). None of this detracts from GMR's significance, but does help to place it in better context.

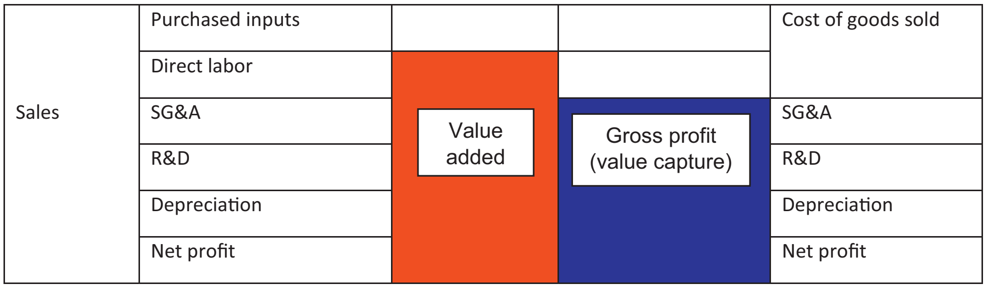

Fig. 2. Components of value added and gross profit.

companies and countries, similar to Gourevitch et al. (2000, p. 305), Dedrick et al. (2009) and Linden et al. (2011).

(1) **Prizes, prestige and patents**. The GMR discovery led to scientific prizes, prestige, and patent revenues for individuals, institutions, firms and countries. Although minor in the context of other measures of value capture, they are important for a full accounting.
(2) **Share of industry revenues**. Revenues and market share provide an estimate of value capture by companies and countries. Although an imperfect measure for countries, given that firms operate in global value chains, it provides a useful measure of the geography of value capture (Gourevitch et al., 2000). We use data on revenues and market share from TrendFocus for 1999-2006, the key production period for GMR-based heads, according to industry experts.
(3) **Gross profits**. Although we would like to use value added, such information is not readily available because publicly listed companies generally do not reveal the amount of their wages for "direct labor" (workers who are involved in converting inputs to a salable product). Instead, the wage bill is combined with the cost of purchased inputs as "cost of goods sold" or "cost of sales." Therefore, the number we use to estimate the value captured by firms in the supply chain is "gross profit," also called "gross margin," the difference between "sales" and "cost of goods sold." Gross profit data are readily available from annual reports in the case of public companies, and we use these company-wide figures for companies to develop our estimates of gross profit. Fig. 2 shows the difference between value added and gross profit, which is the cost of direct labor. The red area covers the items that make up value added and the blue area includes only those that make up gross profit, or value captured by the firm.

Based on company interviews, we estimate that for a $100 HDD, the cost of goods sold is $75. The cost of components is around 85% of the total, direct labor is 8%, and logistics and warranty another 7% (case firm interview). Gross profit is 15–20%. The heads in a disk drive are estimated at 10% of the total cost of components or $7.50. We estimate the profit margins on heads to be in the same range as drives.

(4) **Jobs and wages associated with head manufacturing**. Given that head manufacturing is distributed geographically, we use the number of jobs and the wage bill for different geographies as an indicator of value capture similar to Gourevitch et al. (2000) and Linden et al. (2011). We use data on the number and types of jobs and their location from a single, vertically integrated firm to calculate value capture (Appendix B). We use BLS and other estimates for wages to calculate the wage bill similar to Linden et al. (2011). The data are representative of U.S. vertically integrated firms, and industry experts tell us they are a reasonable approximation for the merchant suppliers as well.

6. Distribution of benefits from GMR

6.1. Benefits to scientists for discovery

Fert received 5 million SEK in Nobel Prize money and other scientific prizes including the Japan Prize (2007) and the Wolf Prize (2007). Fert's biggest gain was support for his research through the new CNRS-Thales Physical Research Unit created in 1995 by the French government's CNRS and the Thales Group (formerly Thomson CSF). The Thales researchers focus on developing products and commercialization, whereas Fert and others focus on research in spin electronics.

Grunberg received 5 million SEK in Nobel Prize money, about $3 million in patent royalties and the Helmholtz professorship (value unknown). He also received about $500,000 for new equipment, but he had already retired in 2004 so the main benefit went to colleagues in his group. The Jurlich Institute received more funding from the German Ministry of Science and Technology and about 10 million Euros in royalties over the life of the patent (Schneider, 2010).

Although he was nominated for the Nobel, Parkin did not receive the award. Parkin was made an IBM Fellow, which is a very high distinction within IBM and currently awarded to only 60 people. He received a large increase in funding for his research, from about $1 million annually to $10 million annually plus another $10 million for new equipment; and a substantial increase in personal salary. He was now a voice that was "heard" within IBM research and therefore better able to influence top executives about research directions (Parkin, 2010). The IBM Research Institute and Hard Drive Research Division work enabled IBM to file around 150 patents related to GMR, but the royalties are unknown. IBM's general policy was to charge firms without much technology between 1 and 5% of revenues for licenses. IBM usually cross-licensed with larger HDD firms that had valuable technology, so there is no way to really know the patent income from GMR (Myers, 2010).

6.2. Benefits to companies

Revenues and market share were a key benefit to companies from commercialization. IBM was never the big winner from GMR technology (Table 2). At the end of 2002, before it sold the HDD division, IBM had only 26% of the $16 billion GMR head market, with $4.2 billion in revenues from 1999 through 2002. Seagate's head revenues (7.5% of its HDD revenues) equaled or exceeded IBM every year but 1999, and earned a 24% market share over the 1999–2006 period.

Although IBM developed the first GMR drive and did the key research for the successor tunneling magnetoresistive (TMR) drives, IBM did not commercialize the latter technology. Instead, it sold the technology and the HDD Division to Hitachi. IBM received $2.6 billion for the physical plant, human resources and patent rights. The only two U.S. head firms remaining, Seagate and West-

Table 2
GMR-based head revenues by firm ($ in millions)

Company	1999	2000	2001	2002	2003	2004	2005	2006	Totals	Mkt. Share
Japanese firms										
Alps Electric	425	324	171	525	719	614	859	705	4,343	11.1%
Fujitsu	420	406	321	135	76	145	12	–	1,516	3.9%
Headway	62	33	-	–	–	–	–	–	95	0.2%
Hitachi Ltd. (HGST)	89	109	118	168	792	903	1,077	990	4,246	10.8%
Hitachi Metals	4	13	–	–	–	–	–	–	17	0.1
Yamaha	93	17	-	–	–	–	–	–	11	0.1
MKE Peripherals	93	197	154	–	–	–	–	–	445	1.1%
TDK/SAE Magnetics	573	894	674	942	1,388	1519	2,333	2,144	10,467	26.7%
Total Japan Sales ($M)	1,760	1,993	1,439	1,770	2,976	3182	4,281	3,839	21,240	–
Japanese firms share of total GMR sales	50%	43%	36%	49%	70%	61%	58%	56%	54%	54%
U.S. firms										
IBM	1,513	1,048	993	614	[a]	–	–	–	4,168	10.6%
Seagate	127	1,073	990	1100	1,145	1361	1,931	1,793	9,521	24.4%
Read-Rite	72	465	532	123	88	[b]	–	–	1,281	3.3%
Western Digital	–	–	–	–	60	683	1,103	1,181	3,028	7.7%
Total U.S. Sales ($M)	1,712	2,586	2,515	1,837	1,293	2,044	3,034	2,974	17,998	–
U.S. firms share of total GMR sales	50%	57%	64%	51%	30%	39%	42%	44%	46%	46%
Total U.S. & Japan GMR Sales ($M)	3473	4,579	3,954	3,607	4,270	5,226	7,316	6,813	39,238	–

Source: TrendFocus via email exchanges in 2014.
Calculations by authors.
[a] IBM sold its HDD Division to Hitachi in 2002.
[b] Western Digital bought Read-Rite in 2003.

Table 3
Gross profits by company (%).

Company	1999	2000	2001	2002	2003	2004	2005	2006	8 yr avg.[a]
Japanese firms									
Alps Electric	20.5	17.8	16.8	n.a.	20.6	18.9	12.9	11.7	17.0
Fujitsu Ltd.	27.9	27.7	28.1	25.5	27.9	26.4	22.3	21.9	25.9
Hitachi Ltd	24.1	26.3	26.9	22.6	23.8	22.3	22.9	21.9	23.8
TDK/SAE Magnetics	29.9	29.5	28.1	19.2	24.5	28.0	26.4	26.3	26.5
U.S. firms									
IBM	36.0	36.3	37.0	37.3	[b]				
Seagate	n.a.	12	20	26	27	23	22	23	21.9
Western Digital	loss	0.5	10.6	13.1	16.3	15.1	16.2	19.1	17.4

Source: Mergent Online and company annual reports.
[a] Seven year average used when data is missing for some years.
[b] IBM sold its HDD business to Hatachi so we do not include its gross profits.

ern Digital, earned a 46% market share in 2006, compared to the 54% share of the three remaining Japanese firms, TDK/SAE Magnetics, Hitachi Ltd., and Alps Electric.

We estimate gross profits for the industry over the period at about $8.1 billion.[6] The Japanese companies had higher gross profits overall than the U.S. firms as shown by the average margins over 1999–2006 (Table 3). The most meaningful comparison of gross profits is between the Japanese companies Alps Electric and TDK/SAE Magnetics on the one hand, and the U.S. companies Seagate and Western Digital on the other. Margins varied from a Western Digital loss in 1999 to a high of 26% gross profit for TDK/SAE Magnetics. The two Japanese firms averaged 21.7% gross profit versus 19.6% for the two U.S. firms.

In addition to the distribution of profits among the head makers, it is important to note that GMR enabled magnetic hard drives to continue to be the primary high performance storage technology due to continuous improvement in areal density and consistent reduction in price per megabyte. These trends have kept the industry highly competitive with solid state storage (Grochowski, 2010) and lower prices have increased the number of units sold, helping industry revenues to increase (Table 2). Consumers and downstream product manufacturers that used HDDs benefited from greater capacity, smaller form factors and declining prices.

6.3. *Benefits to countries*

6.3.1. *Jobs and wages for U.S. head manufacturers*

Given that head manufacturing is distributed geographically, we would like to use the number of jobs and the wage bill for different geographies as an indicator of value capture by country. However, data are not accessible for the merchant or other head firms of Japan. Therefore, we use data on the number and types of jobs and their location from a single, vertically integrated U.S. firm to estimate value capture by jobs and wages (Table 4).

The analysis shows 1.75 times the number of jobs in non-U.S. locations than in the U.S. However, the U.S. jobs are high-paying for both professionals and non-professionals, whereas most of the non-U.S. jobs are much lower paying. Consequently, the wage bill for U.S. workers is nearly 12 times greater than for workers in non-U.S. locations, consistent with work by Linden et al. (2011) and earlier work by Gourevitch et al. (2000).

[6] Total industry revenue of $39,238 billion was multiplied by the average 20.6% gross margin for four firms (Alps, TDK, Seagate and Western Digital), which best capture likely profit margins for heads companies.

Table 4
Jobs and wages associated with making GMR heads at case company[a] (2006).

Type of job by U.S. and Non-U.S. location	Head- quarters /R&D[b]	Head manu- facturing	Head gimbal assembly[c]	Total jobs	Hourly wage $[d]	Total Wage bill $
U.S.						
Professional	270	100	150	520	43.00	44,720,000
Non-professional	30		1,600	1,630	25.65	83,619,000
Total	300	100	1,750	2,150	–	128,339,000
Non-U.S.						
Professional****			250	250	8.00	4,000,000
Non-Professional			2,600	2,600	1.31	6,812,000
Total			2,850	2,850	–	10,812,000
Total U.S. & Non-U.S.	300	110	5,000	5,000	–	143,151,000

[a] The case firm produced about 260 million GMR heads in 51 million HDDs in 2006. The total jobs in the case company were 25,000, with about 5000 in the U.S. and 20,000 outside. The above estimates of jobs along the heads value chain were based on case company interviews, and represent about 20% of the total jobs in the company. There were about 2600 additional jobs in the U.S. related to head stack assembly and final assembly of hard drives for the U.S. market.
[b] Headquarters, R&D and head manufacturing were based entirely in the U.S. at the time.
[c] About 40% of the head gimbal assemblies and hard drives are made for the U.S. market and overseas subsidiaries of U.S. companies.
[d] Headquarters/R&D and Head manufacturing were roughly 90% professional (engineering, managerial and highly skilled technicians) and 10% non-professional. Assembly jobs were roughly 90% non-professional and 10% professional, and located in Malaysia and Thailand.

Table 5
U.S. and non-U.S. GMR heads jobs averaged across two U.S. companies (2006).

Locus of jobs	Case Company	Company B[a]	Average
U.S.	2,150 (43%)	1,620 (18%)	1,995 (30.5%)
Non-U.S.	2,850 (57%)	6,480 (82%)	4,665 (69.5%)

[a] The 2006 annual report for Company B showed it had nearly twice the employees as the case company, and had a much greater percentage of employees outside the U.S. (82%).

Surprisingly, the ratio of U.S. jobs to non-U.S. jobs for the case company was much higher than other researchers studying global value chains have found (Gourevitch et al., 2000; Dedrick et al., 2009). Consequently, we calculated the job mix for another vertically integrated U.S. HDD company and took the average of the two (30% U.S. jobs and 70% non-U.S. jobs), which was more representative of the industry. We have been unable to get similar data for Japanese head manufacturers (Table 5).

6.3.2. Country prestige

The benefit of GMR to France was national pride and celebration of the prestige garnered by award of the Nobel Prize to a French scientist. At the Nobel event sponsored by the University of Paris, President Nicholas Sarkozy remarked that "the Nobel Prize illustrated the benefits of industry and universities working together." In fact, the industry cooperation was the loan of an engineer and some equipment but not real engagement in the research by Thomson.[7]

The German case was similar. By the time of the Nobel award, the Jurlich Institute had shut down the Magnetism Research Center, but kept GMR research at the same level as before. Unlike in France, there was no new well-funded program of industry-university joint research, nor any new research institutes devoted to spintronics. In congratulating Peter Grunberg, German Chancellor Angela Merkel only said, "This proves that good promotion of basic research is the foundation for being able to have internationally outstanding researchers among us" (Germany: Peter Grunberg wins Nobel Prize in Physics, U.S. Fed News Service, October 9, 2007. http://www.highbeam.com/doc/1P3-1373311521.html. Last accessed 12/25/2013).

6.3.3. Country leadership of the industry

The commercialization of GMR by IBM helped U.S. firms take the lead in the head industry from 1999 to 2001 (Table 6). Three U.S. firms—IBM, Seagate and Read-Rite held 49% of the worldwide GMR-head market through 2002. But Read-Rite was losing money and IBM decided to quit the HDD business, which left a big hole in the U.S. industry. Western Digital bought Read-Rite and made a quick comeback while Hitachi bought IBM's business. By 2003, through licensing and their own R&D, the Japanese firms had caught up and had 70% of the world market, but the U.S. share rebounded to 46% in 2006.

Japan was the biggest winner with a 54% overall market share for the 1999–2006 time period OF GMR heads. Although Fujitsu and Hitachi produced their own heads, other HDD makers (including Toshiba) purchased heads from merchant suppliers, such as TDK/SAE Magnetics and Alps Electric, giving them scale economies and the ability to invest in new technologies. Hitachi's purchase of IBM's HDD Division gave them IBM's head production facilities plus its product development and engineering expertise, which helped it become a leader in new technology for a time.

7. Discussion

7.1. Why France and Germany did not benefit from GMR

At the time of the GMR discovery in 1987, the European computer industry was on the wane and the HDD industry, which depended on the former, was dying. The computer industry had been dominated since the 1970s by national champions (ICL, Groupe Bull, Siemens-Nixdorf), which were vertically integrated computer firms each with their own captive hard disk drive operations. The introduction of the IBM PC architecture in the early 1980s shifted firm and industry structure from vertical integration to horizontal segmentation, and from regional supply chains to global ones (Dedrick and Kraemer, 1998; Jacobides et al., 2006). The basis for competition in disk drives shifted from supplying proprietary systems to supplying systems with

[7] While France missed out on the commercialization of GMR in hard disk drives, the French government has created Spintec in Grenoble and CNRS-Thales near Paris to promote spintronics research, prototype development and technology transfer to companies. CNRS-Thales is a joint government-industry laboratory conducting research on various aspects of spintronics, including spin polarized tunneling, magnetic nanowires, semiconductors and spin transfer effects in nanowires. The lab grew out of the collaboration between Fert's team and Thomson-CSF. (http://www.trt.thalesgroup.com/ump-cnrs-thales/presentation.htm. Last accessed 12/26/2013).

Table 6
Worldwide market shares of GMR-head producers by country – 1999–2006.

Country	1999	2000	2001	2002	2003	2004	2005	2006
United States	49%	56%	64%	51%	30%	39%	41%	46%
Japan	51%	44%	36%	49%	70%	61%	59%	56%

Source: TrendFocus, 2014. Calculations by authors.

"...more standard interfaces and architectures, sold increasingly on the basis of cost and availability. Obtaining high volumes became fundamental to achieving low cost.... This favored policies that promoted the development and support of OEM business in addition to captive supply of HDDs. Japanese firms clearly shifted their focus from predominately captive supply in 1982, to a balance of OEM and captive supply by 1986—a shift that European firms did not follow" (Chesbrough, 1999).

The European weakness in absorptive capacity was in their inability to develop commercially successful products. Thomson developed a video cassette product using GMR, but the market was shifting to DVDs and Thomson's product failed. Siemens licensed GMR technology from the Jurlich Institute, and even developed production lines in Germany, but ended up abandoning the market, partly because of the lack of domestic PC or electronics companies as potential customers. They also lacked high volume manufacturing capacity and had not built up the extensive supply base in Southeast Asia that the U.S. HDD companies relied on to bring products to market quickly and at low cost. Much later, in 2008, Siemens sued Seagate for infringing on its GMR patents. Siemens won an award of $160 million in the initial suit, but lost on appeal when it was shown that Seagate had licensed the technology from IBM prior to Siemens' patent, thereby invalidating the patent (Callahan and McQuillen, 2008). Parkin testified on behalf of Seagate in the case.

This supports arguments for the European Paradox, at least in this industry. Dosi et al. (2006, p. 27) point to a lack of absorptive capacity in some European industries when they say: "...quite independently of the 'bridges' between scientific research and industrial applications, potential corporate recipients [in Europe] are smaller, weaker and slower in seizing novel technological opportunities than transatlantic counterparts. This is well highlighted also by those revealing cases where science is world class, all the 'transfer mechanisms' are in place but hardly any European firms are there to convert scientific knowledge into commercial products."

7.2. Why the U.S. and Japan benefited

In contrast to Europe, the U.S. and Japan had greater absorptive capacity in their head manufacturers and HDD industry. The key was having domestic companies with experience in MR technology, the capability to do the required R&D and to bring competitive products to market. Keeping pace with HDD technology was a tremendous challenge. The areal density of HDDs had increased at a compound rate of only 25% per year from 1956 to 1991, but it accelerated to 60% per year with AMR heads and to 100% per year with GMR (Grochowski, 2010).

Historically the U.S. HDD industry started with IBM, CDC and Memorex. Startup firms such as Seagate, Western Digital, Maxtor, Conner and Quantum entered the industry in the 1980s. Most were founded by HDD engineers who left the incumbents, IBM in particular, to start new companies. They were aided by plentiful venture capital, which enabled them to develop competitive products through multiple generations (Christensen, 1993; Chesbrough, 1999).

Many of the firms were located in Silicon Valley, near IBM's San Jose and Almaden research labs and HDD business, and surrounded by the vast electronics industry cluster in that region. This suggests a case of absorptive capacity contained in an industry cluster (Giuliani, 2005), rather than just individual firms. The newer companies moved manufacturing to Southeast Asia in the 1980s, and built up a regional supply and production network that could quickly ramp up high volume, low cost production of new product generations (Dedrick and Kraemer, 1998; McKendrick, 1999; McKendrick et al., 2000). The combination of design and product development skills in the U.S. plus process engineering and production capabilities in Asia sustained U.S. leadership in the industry.

These resources also helped the U.S. industry assimilate and exploit GMR very quickly. "Once the IBM research was out, everybody began working on GMR product development at the same time" (Kryder, 2010). Moreover, talented engineers moved back and forth between firms bringing new knowledge that increased the absorptive capacity of the industry cluster. "The way to succeed was to figure out how to engineer something faster than the other followers" (Re, 2006).

Seagate invested in R&D and licensed technology from IBM to get GMR products to market only a year behind IBM. Western Digital initially licensed GMR from IBM, then bought the failing head supplier, Read-Rite, getting access to its GMR and other head technologies. This meant that the two remaining U.S. HDD makers were vertically integrated, making their own heads and other key components. The modular, horizontally segmented business model that succeeded in the PC and fabless semiconductor industries disappeared in U.S. HDD makers.

For Japan, absorptive capacity lay in the experienced merchant head makers such as TDK/SAE Magnetics and Alps Electric, and with the large Japanese computer firms such as Fujitsu, Hitachi and Toshiba, which were vertically integrated businesses that made drives for their own computer and consumer electronics products. Being able to sell HDDs to many affiliated companies meant they did not have to engage in the same relentless price competition as U.S. companies—at least in their domestic market. However, as global sales became increasingly important to profitability, limited markets and high costs (R&D and production in Japan versus lower cost countries) reduced the profitability of Japanese HDD makers. After the period of this study, Fujitsu and Hitachi exited the market.

The merchant head makers TDK/SAE and Alps also made sensors for applications in many industries, including computers, consumer electronics and appliances and industrial products, which provided them with scale that enabled them to survive the price competition and consolidation in the HDD industry. This broad application gave them profits for investment in R&D and innovation that could be spread across many fields.

7.3. Why IBM left the HDD business

IBM was first to market with AMR- and GMR-based drives, but lost its first mover advantage because it was unable to prevent competitors from acquiring the know-how to implement GMR (in fact it licensed to competitors). Also, the production technology required to build the product was similar to the earlier AMR technology. AMR heads had required changes in a number of aspects of the drive, including the electronics, data format, and head/disk interface design. The way that GMR was used in a drive was the same; even the processes and tooling were the same. Therefore, it was easier for manufacturers that had developed AMR heads to integrate the GMR heads with other drive components.

This similarity of AMR/GMR production technology helped the entire HDD industry to switch to GMR within two years after IBM. Some of the knowledge was published and freely available,[8] and other drive makers, as well as independent head merchants such as Read-Rite, could do the R&D to bring GMR products to market. Seagate licensed GMR from Jurlich and IBM, and soon was producing GMR-based drives.

IBM may also have hurt its cause with its strategy for exploiting GMR. In 1998, it announced agreements to supply Maxtor and Western Digital with GMR heads and other components and designs to integrate GMR technology. Selling heads as an OEM at the same time it introduced GMR in its own products allowed IBM to generate additional revenue, but it gave competitors access to IBM's technology. IBM might have slowed its competitors with more aggressive intellectual property protection, but this likely would have conflicted with IBM's IP strategy for its large portfolio of technologies.

At the same time, hard drives were becoming commodities with brutal price competition driving down gross margins. In 1999, Maxtor's gross margin was just 8% and Western Digital's gross margin was negative 0.1% (annual reports). IBM didn't report separate revenues or margins for its HDD business but it was competing in an industry which could barely cover its production costs, to say nothing of R&D and overhead expenses. At this time, IBM was moving strategically to shift out of commodity hardware and focus more on software and services and IBM finally sold its HDD business to Hitachi in 2002.

8. Theoretical implications

The GMR case is consistent with some of the major arguments of the absorptive capacity literature. It confirms the *value of experience with related knowledge* (Cohen and Levinthal, 1990), specifically the knowledge of MR heads and the specialized manufacturing knowledge needed to produce them.

It also confirms that weak appropriability regimes and the availability of external knowledge leads firms to invest in absorptive capacity. It is not consistent with the argument that absorptive capacity needs to be accumulated over time and is firm-specific. Instead, the case shows that even complex *knowledge can be transferred across firm boundaries* through licensing, mergers, and hiring people with the requisite knowledge.

The case also illustrates the importance of appropriability in determining the ability to profit from innovation (Teece, 1986). The ease of entry into the industry and the relative openness of knowledge limited the ability to use absorptive capacity to gain sustained competitive advantage. Only after a long period of consolidation were the survivors able to earn steady profits while continuing the pace of innovation. However, the argument for industry environment as a key determinant of capturing value is more complex, as we discuss below.

To understand better the dynamics of how new knowledge is translated into commercial products, and who captures value, requires looking very closely at the details of a case. When we do so in the GMR case, we uncover insights related to knowledge characteristics, industry characteristics, and the relationship between firm and country-level value capture in a global industry.

8.1. Knowledge characteristics

A question raised by some interviewees is whether GMR was a transformative discovery, or simply an incremental step in the stream of MR innovations from AMR to GMR to TMR. From the scientific point of view, GMR was a major advance (evidenced by the Nobel Prize), and Parkin's scientific breakthroughs played a critical role in exploiting it. Consistent with Cohen and Levinthal's (1990) argument that *experience with related knowledge* is a predictor of absorptive capacity, IBM's long-term investment in MR technologies gave it absorptive capacity needed to assimilate and commercialize GMR. A key point here is sharpening the ability to distinguish whether a firm's existing knowledge is related to the new knowledge. We point to the concept of competence-enhancing versus competence-destroying disruptions (Christensen and Rosenbloom, 1995) to make this distinction. GMR was a new type of knowledge, yet its exploitation drew on IBM's existing scientific knowledge, engineering knowledge and manufacturing capabilities. As such, it was competence-enhancing, and IBM clearly had extensive related knowledge.

However, the nature of GMR knowledge was such that it could be licensed and applied (e.g., by Read-Rite, Seagate and Headway), and it could be carried from one company to another through IBM scientists (e.g., by Headway and others), or acquired through buying a company (e.g., Western Digital and Read-Rite). The ability of other head makers to assimilate and exploit this knowledge without IBM's long investments in R&D (and in fact benefiting from IBM's investments) contradicts Cohen and Levinthal's (1990) argument about the firm-specificity of knowledge and the difficulty of accessing external knowledge through these paths.

8.2. Industry characteristics

To understand why the industry could not translate its rapid innovation into sustained profits, we must look at the industry structure and its impact on value creation and capture. The HDD industry has sustained improvements in price performance that top even the semiconductor industry with its famous Moore's Law. From 1988 to 1998, the cost per megabyte of storage fell from \$11.54 to \$0.04, (Porter, 1998) a pace which enabled the hard drive to remain the primary storage technology in PCs, and to be incorporated into other electronic devices. The progression of head technology from AMR to GMR along with major improvements in other components helped create enormous value for the computer industry and its customers. Yet profits eluded most HDD and head makers, and most of the value was captured by its customers, and by the end consumer.

Throughout its history, the industry has experienced continuous churn, with over 200 companies making HDDs at one time or another (Porter, 1998). With each succeeding shift in platform, from 14-inch to 8″ to 5.25″ to 3.5″ to 2.5″, new leaders emerged and old ones failed (Christensen, 1993). In 1990, there were 59 firms making hard drives, a number that dropped to 16 by 1998 (Porter, 1998). The ability of any firm in the industry to appropriate value was weak. Products were judged by customers on performance, price and reliability. Firms could capture a brief period of profits if they came out with a newer generation of product a few months ahead of their competitors, but would not make any profit if they were late. Knowledge flowed freely in the close-knit community, with engineers publishing discoveries to enhance their own reputations, and often moving from one firm to a competitor. Branding had little value, and switching costs for customers were

[8] IBM scientists and engineers (and others) published their work on a regular basis in physics, magnetism and IEEE journals, so information was available to other experts. See for example: Parkin's 1992 discussion of his basic research findings. Also see Tsang et al., 1994 for a description of their product development work.

very low as all drives had to be made to standards set by the PC industry.

The only way for the industry to escape its near-suicidal pace of competition was continued consolidation (Fujitsu, 2009; Seagate, 2011; Ribeiro, 2012). Firms had to acquire or be acquired until the field was so small that the remaining firms could hold prices at profitable levels. From 1998 to 2014, this is exactly what happened. The remaining companies making heads are Seagate, Western Digital, Toshiba, TDK/SAE Magnetics and Alps Electric. Since the mid-2000s, the remaining firms have maintained gross margins around 20% or higher and have been profitable each year (Table 3 above).

The GMR case illustrates the importance of the regimes of appropriability in an industry (Teece et al., 1997), and also provides insights into specific factors that influence appropriability. When appropriability is low, imitation by rivals is rapid and widespread and, therefore, payoffs from innovation may be low. In the HDD industry, patents are used more for cross-licensing rather than to block competitors from using new knowledge, and there is little opportunity to differentiate a product or create switching costs. But it is one thing to talk about worker mobility or IPR (intellectual property rights) practices, and another to explain them. In terms of IPR, HDD and head makers were encouraged to cross-license rather than pursue costly (and possibly unsuccessful, as in Siemens' case) legal action. Also, the original GMR patent was held by Jurlich, which had an incentive to license freely and maximize its fees. Another point rarely raised is that the need for the whole industry to match or surpass the rapid performance gains of solid state memory chips may have encouraged a degree of cooperation. Most rapidly evolving technologies do not need to stay ahead of an industry that doubles its performance/price every 18 months as the semiconductor industry does, but the HDD industry did. Also, the culture of the U.S. industry encouraged scientists and engineers to take their knowledge and start new companies, the availability of venture capital facilitated the process, and the close networks of professionals in the industry made it difficult to keep secrets. The Japanese firms could afford to be a bit behind because most had large captive internal markets, and had access to cheap capital within their industry groups or *keiretsu*. The exception was TDK, which took a very American approach by acquiring Headway and its combination of HP knowledge and IBM people.

8.3. Determinants of value capture by countries

The absorptive capacity literature has not examined deeply the determinants and nature of absorptive capacity at the country level. We look at several forms of country benefits, including jobs, wages, prestige, and industry leadership. The most important determinant of country success is the presence of firms that can assimilate and commercialize new knowledge. Their gross profits mostly stay in the home country, supporting well-paying jobs in R&D, product design, administration, sales and marketing, as well as rewarding investors.

The other main factor for country success is being part of the global value chains of leading firms. This may depend initially on low wages, but over time countries can develop important capabilities that go beyond low costs. Singapore started out as a low-cost production site for several HDD makers, but as production moved elsewhere in Southeast Asia, it became a hub for global firms managing their regional supply and production networks. The ability of the region to move a product from design to full-scale manufacturing in a short time was critical in the industry. Once the region had established these capabilities, it retained its central role even as the names of the companies changed. Even the Taiwan/China hub that came to dominate other parts of the electronics industry did not pull the HDD industry out of Southeast Asia.

Table 7
GMR-based head revenue and gross profits by country, 1999–2006 (millions).

Country	Revenue	Gross margin	Gross profits	Share of gross profits
U.S.	$17,998	19.6%	$3527	43%
Japan	$21,240	21.7%	$4609	57%
Total	$39,238		$8136	100%

Source: Author estimates from TrendFocus data.

9. Policy implications

It is clear from this case that the economic benefits from scientific discovery may go to the companies and countries that commercialize technology rather than to the individuals, institutions and countries that make the scientific discovery, as noted by Pavitt (2001). The scientists who discovered GMR received the prestige of a Nobel Prize and the Jurlich lab received an additional $10 million Euros in royalties; the only other benefits to Germany or France came from IBM's facilities in Mainz, Germany, which ran the company's storage business in Europe and manufactured heads and drives. While the U.S. led introduction of GMR heads, Japanese firms captured the greatest economic benefit: $21 billion of the $40 billion head revenues and $4.6 billion out of $8.1 billion gross profits from 1999 to 2006 (Table 7).

The GMR case supports Mansfield's (1996) argument that a nation's economic performance depends on how well its firms can commercialize research to bring about profitable new products and processes. How then can a country increase the chances that its firms can exploit knowledge created either by its own scientists, or those outside its borders, to bring about profitable new products and processes? The determinants of value capture by countries – the presence of firms with absorptive capacity and their participation in global value chains – suggest several policies.

Countries can help their firms and industries by creating a good environment for absorptive capacity to develop. The U.S. policy environment is favorable to venture capital and new company formation, has strong intellectual property mechanisms, and makes mergers and acquisitions relatively easy. This environment supported a dynamic HDD industry that led the world in creating and exploiting new knowledge.

Trying to protect incumbent firms, as France and Germany have done in the computer and electronics industries, can make them uncompetitive internationally and unable to keep up in fast-moving industries such as HDDs. Europe also did not encourage foreign firms to invest in its technology industries; in fact, for many years policy in some European countries focused on keeping IBM from dominating their IT markets. IBM Europe included Mainz as part of its global HDD business, but when it sold that business to Hitachi, the HDD business was moved. By contrast, Northern Ireland has been more supportive and is a major production location for Seagate. Singapore and other Southeast Asian countries have benefited from incentives provided to attract foreign HDD companies which have created tens of thousands of jobs in the region (Linden et al., 2011). Those countries now have a rich absorptive capacity in rapid ramp-up of high volume production of new HDD technologies which has helped protect them from competition from lower wage countries.

The case suggests that countries can increase their companies' absorptive capacity by *creating research infrastructure for capturing external knowledge and disseminating it to domestic firms*. Learning from its missed opportunity, France created the Spintronics Research Institute to (1) monitor scientific and engineering developments that might be opportunities for domestic firms and (2) engage in precompetitive research and development related thereto. At the same time, the INRS (National Institute for Scientific Research) continued to support small scale experimental research by Fert and others. Already in the 1980s countries such as Taiwan and Singapore created institutions to facilitate technology transfer from multinationals and its assimilation by domestic firms. In Taiwan, the Information Technology Research Institute developed capabilities in local firms and the Institute for the Information Industry trained staff and helped to develop the domestic market for local and multinational firms. In Singapore, it was the Economic Development Board and the National Computer Board (now the Infocom Development Authority). These institutions enabled domestic firms to develop basic capabilities, and through continuous upgrading, to become an integral part of the global value chains of the HDD industry and the broader information technology industry (Dedrick and Kraemer, 1998; Ernst and Kim, 2002). At the same time, they increased the competitive capacity of their multinational partners in a dynamic, rapidly changing industry.

The case further suggests that in-country and in-house R&D capability, whereby external knowledge can be assimilated and transformed into new products and services, is needed by firms in order to exploit external scientific discoveries. Both the U.S. and Japanese firms invested in their own R&D, which enabled them to make the transition to GMR on the heels of IBM, to be first with follow-on innovations and to move up the path of technology development. These investments were stimulated by country policies to promote private R&D, such as R&D tax credits in the U.S. and similar incentives in Singapore and Taiwan. Such incentives have been the subject of considerable debate, as they may pay companies to do research they would have done anyway (Mohnen, 2012), but there is considerable evidence that they lead to greater private R&D activity (Bloom et al., 2002; Tyson and Linden, 2012). Whether this leads to more successful corporate innovation is not clear, but economists estimate the social return on investment of public funded R&D from a low of 30% to over 100%, and the social return far greater than the private return (Jones and Williams, 1998).

It is likely that none of these policies alone will lead to success, but in concert with one another—favorable country environment, research infrastructure, human capital and R&D investment, there might be a greater possibility for success for companies and countries in exploiting scientific innovation in a global economy. Even then there is no way to deal with the problem of missing firms in cases "...where science is world class, all the 'transfer mechanisms' are in place but hardly any firms are there to convert scientific knowledge into commercial products" (Dosi et al., 2006).

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Appendix A. Literature on absorptive capacity

Literature on absorptive capacity

Table A1 Selected conceptual and empirical studies of absorptive capacity.

	Methods and data	Treatment	Framing	Contributions
Firm				
Cohen and Levinthal, 1990	Quantitative, 1719 manufacturing firms	Definition and antecedents of AC	Organizational learning	DR&D and experience with related technologies create capacity to assimilate and exploit technology
Boynton et al., 1994	Quantitative, 132 firms	AC as predictor of IT use	Managerial knowledge, process	Managerial knowledge is key predictor of IT use
Cockburn and Henderson, 1998	Quantitative, 68,186 publications and citations	Firm access to upstream basic research	Industrial economics	Connectedness with scientific community is correlated with firm innovation performance
Lane and Lubatkin, 1998	69 alliances of pharmaceutical and biotech firms	Relative absorptive capacity of firm dyad's	Interorganizational learning	Similarity of partners' knowledge, structure and practices increases ability to learn from partner
Zahra and George, 2002	Conceptual	Antecedents, dynamics, outcomes of AC	Dynamic capabilities	Potential & realized AC; AC as dynamic capability; appropriability& competitive advantage
Matusik and Heeley, 2005	Quantitative, 180 software firms	Internal and external dimensions of AC	Interorganizational learning	Relevant public industry knowledge and transfer routines increase private firm knowledge
Escribano et al., 2009	Quantitative, 2265 Spanish firms	Impact of AC on competitive advantage	External knowledge flows	AC is a source of competitive advantage, esp. in turbulent sectors with strong IPR
Business unit				
Jansen et al., 2005	Quantitative, 769 org units in financial services	Antecedents of potential and realized AC	Organizational behavior, coordination	Coordination capabilities enhance potential AC, socialization capabilities enhance realized AC
Country				
Mowery and Oxley, 1995	Conceptual	AC as moderator of inward tech transfer	National innovation systems	Innovation, productivity greater for countries that invest in AC
Castellacci and Natera, 2012	Quantitative, 87 countries from 1980 to 2007	AC interaction with innovative capability	National innovation systems (NIS), growth economics	Coevolution of innovative capabilities and absorptive capacity drive national innovation and economic growth

Appendix B. Methodology

Methodology

This appendix details our methodology for calculating estimates of jobs and wages associated with head manufacturing for a vertically integrated U.S. HDD manufacturer for the year 2006.

Our task was complicated by the fact that we were looking at jobs associated not with an industry, but with part of the HDD value chain for small form factor drives (e.g., 2.5"), similar to the situation in the iPod study by Linden et al. (2011). To arrive at our estimates, we used a "case" company which we created through interviews, analysis of company reports, similar government data, data from industry analysts, and other sources. We were conservative about the U.S.-non-U.S. gap by "rounding up" overseas estimates and "rounding down" for the United States.

1. Job estimation

We began with an estimate of the jobs associated with a factory that produced 12 million HDDs per quarter broken down according to activities in the HDD supply chain as shown below. A firm producing about 50 million drives annually would employ about 25,000 people broken down as shown below.

Table B1: Jobs by Activities in hard drive manufacturing.

Heads			Other manufacturing, assembly and support							
HQ/R&D/S&M	Head mfg.	Head gimbal assembly	Head stack assembly	Disks Mfg.	Motor Mfg.	PCBA Mfg.	Enclosure Mfg.	HDD assembly	Logistics/ warranty/tech support	Total
2000	100	4000	4000	5000	4500	500	600	4000	300	25,000

In developing job and wage estimates we focused on that portion of activities that would be associated with heads, shown in grey above. We also determined how many jobs were U.S. versus non-U.S. Interviews indicated that about one fifth (5,000) were in the U.S. and four-fifths (20,000) outside. We then divided the jobs among higher- and lower-paying job categories, as discussed below.

We now present a more detailed description of the process:

1. We began with estimates of the total number of jobs associated with producing 12 million HDDs a quarter for our case firm. We annualized the total to 60 million HDDs a year with an average of 2.3 heads per drive.
2. For the number of heads workers at points along the value chain, we derived estimates from interviews, and confirmed these estimates with other interviews and industry experts.
3. For higher-paying engineering and management jobs, our estimates were based on firm interviews and site visits, wherein we developed ratios of engineering and management staff to manufacturing jobs. Applying these ratios to the staff estimates enabled us to generate estimates of the number of managerial and technical people related to each point along the head value chain. For example, in a U.S. head manufacturing facility, roughly 90% the workers were highly-paid professionals (skilled technicians, engineers and managers). In contrast, in a non-U.S. head gimbal for final assembly factory, 90% of the workers were lower skilled production workers and only 10% were professional workers.
4. For the head-specific jobs at the case firm, which included many high-paying jobs in. software, marketing, and administration, we chose a conservative 10% based on three estimates of the percentage that heads represent in the total value of a HDD – an outside reviewer and an executive in our case firm at 10%, and our own calculation at 14%. We used 10% to be conservative. Our method for determining the distribution of jobs among several pay grades of professionals and non-professional employees is described below under "Wage estimation."
5. We did not estimate the jobs associated with retail sales by the case firm or others, as heads are not sold via the retail channel, although HDDs are sold this way. Similarly, since this firm produces heads only for its own use, there is no sales and marketing activity related to heads, although there is such activity related to the final hard drive product.

Wage estimation

For non-U.S. jobs, we used the following sources for the wage rates in Table 4.

Nonprofessional: The nonprofessional earnings were based on the hourly rates for production workers given in table 2 of the Bureau of Labor Statistics (BLS) news release "International Comparisons of Hourly Compensation Costs in Manufacturing, 2006" (http://www.bls.gov/news.release/pdf/ichcc.pdf). Thailand was not listed, so we assumed the same $8 rate as Malaysia. The 2006 hourly rates were annualized by assuming 2000 paid hours per year.

Professional: We used "professional" to designate all higher-wage jobs, including managers, engineers and highly skilled technicians. The "professional" wages in Table 4 were based on engineering salary estimates reported in Dedrick and Kraemer (2008, Table 5). For the countries not covered there (Thailand), we extrapolated based on our knowledge of the level of development of the electronics industry in each country, as well as consulting salary reports about other professional job categories. We liberally rounded the estimates upward so as not to overstate the difference with the United States.

To estimate overhead employment, we started with a ratio of 12%, which is in between two estimates of the head share of the total value of a HDD, and applied it to the case firm's total employment of 25,000 for 300 HQ/R&D workers (including engineers).

To calculate the total wage bill, we applied the national average wages for each job category in the BLS data to our employment estimates. To be conservative, we capped these job categories at the $85,000 wage similar to Linden et al. (2011).

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