Open Innovation and Patterns of R&D Competition

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Abstract

We explore the technological evolution of three microprocessor firms between 1976 and 2004. We trace how two initially small entrants (Intel and AMD) competed against a larger and more established incumbent (IBM). We show that changes in inter-firm relationships (as reflected by competitive and cooperative events) affect patenting strategies. Periods of increased competition correspond to greater patenting within patent classes in which the firms compete head-on. Periods of cooperation are surprisingly not always accompanied by increased patenting in complementary upstream and downstream areas. Despite changes in competitive regime, Intel and AMD exhibit a persistent dependence upon IBM for technology. Our study shows that small firms can compete against a large incumbent in the product market while being dependent upon external sources for knowledge. We also suggest ways in which incumbent firms operating in such environments (e.g., IBM) might engage with these entrants through co-opetition and open innovation.

1. Introduction

Open innovation is attracting increasing academic interest. This special issue of the IJTM is the latest instance. An earlier special issue of R&D Management (June of 2006) and a recent book by Chesbrough, Vanhaverbeke and West (2006), have also called attention to this growing interest. In that book, Chesbrough (2006) defines open innovation as "…the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively". Yet the evidence supporting the phenomenon of open innovation remains underdeveloped. There also has been little examination of open innovation in the context of strategic interactions by small firms in the presence of larger rivals. Here, the "openness" of open innovation raises the issue of whether such strategies are feasible.

We examine the pattern of competition over a 28-year period among three leading firms, IBM, Intel, and AMD in one of the most technologically-intensive industries, semiconductors. We chose this industry in part because it is one in which technology advances rapidly, and where technological capability can confer decisive competitive advantage to firms. The firms are highly asymmetric: Intel and AMD were small startup firms in the late 1960s, entering into a market dominated by IBM which was by then a large, vertically-integrated incumbent firm. We investigate the patenting behavior of each of the firms, in light of shifts in competitive posture, to see whether competition and cooperation in the product market influenced their R&D strategies and knowledge interdependence.

We find that the R&D strategies of the three firms differ significantly from one another, and that these differences persist throughout the period of our study. This persistence is even more striking given the shift in fortunes among the three firms. IBM has a long history of pursuing a research-driven strategy, which resulted in the greatest number of patents, and the broadest range of patents, among the three firms. By the late 1980s, even as IBM's semiconductor sales fell relative to those of Intel and AMD, IBM's patenting behavior persisted. In contrast, Intel's research strategy is commercialization-driven, resulting in fewer patents per dollar of R&D, and a narrower range of patents than IBM, even after Intel's semiconductor sales overtook those of IBM in the late 1990s. AMD's research strategy is even more commercialization-oriented than that of Intel. Over the course of our study, AMD competed head-on against Intel and grew increasingly close to IBM. AMD's patents are the most specialized of the three companies, in that its patents fall mainly into a narrow domain of patent activity (which we will explain later in the paper).

Another focus of the paper is our attempt to examine separately the effects of competition and cooperation along different parts of the value chain. Specifically, we sort the companies' patents into three domains of interest: upstream technology, competitive technology, and downstream application technology. Here we find that IBM and Intel, which experienced rising and falling intensity of competition during the study, follow patterns of "co-opetition" (Brandenburger and Nalebuff, 1996). Intel's patenting shifts towards more complementary regions (upstream and downstream, vs. competitive) when rivalry abates, and returns to more competitive activity as rivalry intensifies. AMD, while intensively competing with Intel throughout the period studied, moved towards a greater level of cooperation with IBM over time, and this is reflected in its focused patenting in competitive technology fields, coupled with an increase in complementary upstream patenting activity.

We also explore the extent to which changes in the product market affect inter-firm knowledge dependence, and we find that although the three firms go through periods of cooperation and/or competition, knowledge interdependence remains basically unchanged, with AMD and Intel depending heavily on IBM, which in turn does not exhibit a high level of reciprocal dependence.

Our findings suggest new directions for theories of technological competition. One implication is that models of strategic choice should expand beyond "compete or collaborate" to consider alternative modes of co-opetition. The co-opetition we observe among IBM, Intel and AMD involves a highly asymmetric pattern with Intel and AMD depending heavily on IBM for knowledge, but not vice-versa. More broadly, we find that knowledge sources for the three firms are far more diffuse than that possessed by the leading semiconductor firms. Third parties, especially universities, research consortia, and even individuals, provide highly useful sources of industrial knowledge. In such instances, upstream technology development will be only loosely coupled to downstream product market competition, consistent with an "open innovation" (Chesbrough, 2003) model of technological advance. We present several suggestions on how an incumbent firm like IBM might have responded more effectively against nimble entrants (such as Intel, AMD) by taking a more open approach to exploit complementarities with such rivals so as to develop co-opetition, especially since these rivals also depended upon the same knowledge base as IBM.

In the next section, we review the literature on open innovation and co-opetition. Then in Section 3, we present a qualitative analysis of periods of cooperation and competition among the three firms. In Section 4, we present a quantitative analysis of patenting behavior by the three firms. Given the limited sample size, we employ this as a way to explore patterns of behavior by the firms rather than a test of hypotheses (e.g. see Ryall and Sampson, 2008). Section 5 presents our interpretation of these patterns, and Section 6 concludes.

2. Openness, Competition and R&D Strategies

The literature on open innovation grew out of a recognition that firms need to leverage both internal and external knowledge in order to innovate (Cohen and Levinthal, 1990; Rosenberg, 1994). Based on several case studies, Chesbrough (2003) identifies key elements of an open innovation process: form relationships to the external scientific community, rely on venture capitalists not just for funding but also to create new learning opportunities, manage intellectual property to extend a firm's technological reach, create internal competition for the metabolism of new knowledge, and leverage internal R&D to establish new architectures and business models.

While Chesbrough (2003) presents "open innovation" as a broad concept, much of the subsequent research on implementing this idea has implicitly focussed on issues relevant to large, incumbent firms. For example, Christensen (2006) explores how open innovation fits in with the core competencies of large firms, while O'Conner (2006) examines the role of open innovation in overcoming difficulties of adopting radical innovation within large established firms. Among the business models proposed such as by Chesbrough (2006) and West and Gallagher (2006), some are appropriate across firms (licensing, selling or leveraging complements), while others would be difficult for a small firm to implement due to resource constraints (spin-outs, acquisitions, pooled R&D).

Intellectual property is heavily emphasized in the open innovation literature. However, it remains unclear whether strong IP is favorable (Rivette and Kline, 2000) or whether appropriability may retard innovation (West, 2006). Much of the research on the role of IP in open innovation is conceptually driven, such as the interesting tradeoff between creating value and capturing value (Simcoe, 2006), but further work is needed to understand how smaller firms might develop portfolios of patents and other intellectual property. The heavy conceptual focus also means there is room to develop novel empirical analysis, especially at the dyad-level (Vanhaverbeke, 2006), and to go beyond the software industry which has been heavily explored by scholars of open innovation (e.g., Henkel, 2006; Graham and Mowery, 2006).

So, while prior research offers valuable lessons, it sheds relatively little light on whether smaller firms can successfully make use of external knowledge (including that of larger rivals) in order to compete in the marketplace. Moreover, little is known about how competition and cooperation in the product market relate to strategies for managing technology, including IP and patenting strategies. And while scholars have also begun to explore the effects of open innovation on inter-organizational networks (Vanhaverbeke, 2006; Simard and West, 2006; Maula et al., 2006), competition and cooperation has yet to be made a central theme in that stream of work.

In this paper, we examine how cooperative or competitive events in the product market relate to efforts by smaller rivals (Intel, AMD) to develop patentable innovations and compete with a large incumbent firm, IBM. We use qualitative methods to analyze how these firms competed or cooperated with each other over time, and we use patent data to quantitatively analyze each firm's IP portfolio and patterns of knowledge interdependence.

We draw upon models of co-opetition in strategy research (Brandenburger and Stuart, 1996). In contrast to earlier work by Porter (1981) and others, Brandenburger and Nalebuff (1996) argue that a firm can have multiple roles in its value net of business. It is possible for a firm to be another firm's supplier, customer, competitor and complementor all at the same time. This is especially important in industries with rapid technological obsolescence, as it allows firms to be nimble.

A key implication of this view is that competition and cooperation may vary along the value chain. Thus the R&D strategies of firms are likely to depend upon whether the innovation is in an area they compete head-on against each other, or whether these investments are made upstream, downstream or in other areas, where there is greater opportunity for collaboration. In the models of Arora et al., (2001), and Gans and Stern (2003), firms can buy and sell technologies in the upstream technology market in addition to - or in lieu of - entry in the product market. Hence, such models end up with a richer set of outcomes than earlier models, in which the winning firm captures the entire market.

Another important insight from the co-opetition literature is that timing is important. Firms involved in co-opetiting relationships may compete during certain periods of time and cooperate during other periods (Brandenburger and Nalebuff, 1996). By looking for transitions between eras of competition and cooperation among a small number of firms (IBM, Intel, and AMD), we hope to better understand how these relationships evolve and affect the firms' R&D strategies.

3. Competition and Openness in the Semiconductor Industry

In this section, we describe the semiconductor industry and identify events that characterize periods of cooperation and competition among IBM, Intel, and AMD.

3.1 The Semiconductor Industry

Since the inception of the semiconductor industry, there has been a rapid rate of entry of new firms. Industry reports show that market concentration is much lower than than in a monopoly or duopoly. Gartner Dataquest (2006) estimates that market shares of leading firms are quite low: Intel (12%), Samsung (7.9%), Texas Instruments (4.5%) and Infineon (4.0%). The Herfindahl index for semiconductor sales is only around 0.053.

A second issue is the connection between the upstream market for technology (Arora, et al., 2001) and the downstream product market. We calculated the number of patents assigned to semiconductor firms by the US Patent Office and found that the top ten firms hold less than 50% of semiconductor patents; the majority of patents are held by other firms and institutions, such as universities, consortia, and even individuals who do not participate in the product market. Thus, the relationship between upstream technology market and downstream product market is one of loose coupling.

A complex relationship exists between patenting and scientific publishing by semiconductor firms (Lim, 2004). IBM leads the industry both in terms of the number of basic scientific contributions its employees have authored or co-authored in scientific research journals, and in terms of the number of semiconductor-related patents it has received. AT&T occupies a similar position to that of IBM, with many basic research articles and many patents, though it lags IBM on both dimensions. However, both IBM and AT&T are highly atypical. Intel and AMD are more similar to other industry participants. Intel's employees author or co-author relatively few scientific research articles, yet Intel receives a fairly sizable number of patents.

Another feature of the semiconductor industry is the complex and cumulative nature of its technology (Brusoni et al., 2001). This leads to a high rate of patent trading among firms (Hall and Ziedonis, 2001), which is consistent with the possibility in this case that the product market is sufficiently decoupled from the market for technology (e.g., see Gans and Stern, 2003).

3.2 Mapping Cooperation and Competition over Time

We qualitatively analyze the relationships between IBM, Intel and AMD to identify periods of competition and cooperation among them. We focus on these firms because they have been the most active competing and/or cooperating in a well-defined area of work: the design and manufacture of microprocessor chips for personal computers. Hence, we are able to observe relatively clearly the patterns of cooperation and competition among these firms over time.

Case histories of each firm were obtained by collecting news reports and annual reports, as well as through interviews with industry sources. Figures 1 and 2 present chronologies of the key events. We have classified each event as either "cooperative" or "competitive" based on the way in which it affected the relationship between each pair of firms.

[Figures 1 and 2 about here]

IBM's relationship with Intel in the semiconductor product market began in the late 1970s, when it selected Intel's 8088 microprocessor to be the processor for its upcoming line of personal computers, which IBM launched in 1981. Gordon Moore, the founder of Intel, would later recall that his firm did not view being selected by IBM as being all that important at the time (Moore, 1996). By 1983, IBM had overtaken Apple as the largest company in the PC industry, and IBM contributed to an increasingly large portion of Intel's revenue and profit. However, Intel struggled in other parts of its business, particularly the DRAM market, such that its financial health was in a precarious state. Since IBM depended upon Intel as the primary vendor of the microprocessor for its PCs, IBM decided to invest $250 million to acquire 12% of Intel's stock in 1983. IBM made this investment to help Intel weather its financial difficulties, and to assure itself of a continued supply of microprocessor chips for its PC business. When Intel's financial condition began to improve in 1986, IBM sold off its stake.

This pattern of cooperation was reinforced by the contractual relations between the two firms. In 1982, IBM forced Intel to second source its 80X86 architecture to AMD[1], and also to grant IBM a manufacturing license for the device family, as a condition of being the key chip supplier for the IBM PC. Intel honored this arrangement with both the 8088 and 80286 microprocessor, but began to drift towards a more combative stance with its 80386 (around 1986). It continued to license IBM for manufacture of the chip, but discontinued the second-sourcing agreement allowing AMD to act as a second source for IBM. This led to litigation between Intel and AMD, but Intel continued to license IBM with the 80486 chip as well.

The climate of cooperation between IBM and Intel further worsened as IBM's position in the PC market evolved. As the PC industry expanded, IBM progressively lost control over the PC architecture (Langlois, 1992; Ferguson and Morris, 1993; Chesbrough and Teece, 1996). In 1986, Intel launched its 80386 microprocessor, and Compaq (not IBM) became the first PC manufacturer to ship the 80386. At the same time, Microsoft began to develop its Windows operating system, which would gradually diverge from IBM's OS/2 architecture. IBM's MicroChannel bus architecture that was introduced in 1987 also failed to take hold, and Intel's rival PC-Bus architecture became established by 1990 as the next successful platform for personal computers (Cusumano and Gawer, 2002). On each of these critical elements of the PC architecture, IBM lost its ability to lead the industry. PC-compatible manufacturers began to gain market share from IBM, and IBM's PC business became less and less profitable. While IBM's power in the PC market diminished, Intel grew from strength to strength. In line with this growth, Intel began to invest significantly in its own R&D capabilities (see Figure 3), spending practically nothing in the 1980s but almost US$4 billion by the year 2000.

[Figure 3 about here]

The relative fortunes of IBM and Intel changed in the 1990s. IBM's semiconductor sales were overtaken by those of Intel in 1991, and IBM's spending on semiconductor R&D was overtaken by that of Intel in 1995.[2] Yet, while Intel overtook IBM in absolute spending on semiconductor R&D, the intensity of its investment continued to lag behind IBM. "Historically, IBM did its own research, and Intel

[1] See http://www.amd.com/us-en/Weblets/0,,7832_12670_12686,00.html

[2] Source: Dataquest reports and Intel Labs (A) Case (Chesbrough, 1999).

historically did not," said David Tennenhouse[3], former Vice President of Research at Intel. "And much of the research we did do was intended to help us understand the other research out there, whereas IBM was trying to commercialize its own research."

IBM did not passively cede control over the architecture it created to Intel. While IBM continued to purchase Intel microprocessors for use in its PC systems, IBM also initiated new projects that changed the character of its relationship with Intel. IBM exercised its manufacturing license on the Intel 486 to begin its own manufacture of Intel compatible microprocessors[4], reducing Intel's revenues at IBM. IBM also began to sell these microprocessors to other computer makers, putting it in direct competition with Intel. IBM even began working with Intel rivals, trying to help them compete as alternate sources of Intel-compatible microprocessors. In 1990, for example, Intel sued Cyrix, which worked with IBM to create an Intel-compatible microprocessor, and in 1994 IBM started to produce Cyrix chips for internal use and for sale on the open market. In 1996, IBM began to use AMD's chips for notebook computers and its Aptiva desktop computers, and ever since then, IBM has chosen AMD chips for use in its computers.

IBM also tried to compete with Intel by collaborating with Motorola and Apple starting in 1991 to create an alternative architecture for the personal computer – the PowerPC – which was used in supercomputers, numerous embedded applications, as well as the Apple Macintosh (until 2005).[5] In turn, Intel terminated IBM's manufacturing license to its technologies with the introduction of its Pentium generation microprocessors in the early 1990s, making Intel the sole source of the chip. IBM's PC business was now just another customer of the Intel Pentium processor.

Towards the end of the 1990s, Intel and IBM began to diversify their activities. New applications emerged for semiconductor chips in computer networking, telecommunications, and consumer products, so that the chip market had evolved from a single battlefield into several profitable segments. Competition between Intel and IBM continued to intensify. For example, In 2002 IBM and Intel began to compete

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[3] Personal interview with one of the authors, November 23, 2006.

[4] IBM had a technology cross-licensing agreement with Intel that precluded Intel from suing IBM for its actions.

[5] IBM also purchased Metaphor Computer in 1991, and formed Patriot Partners, to develop a rival operating system to Microsoft Windows, and formed a second company, Kaleida, to create new graphics standards for the PC. These initiatives, though, also proved unsuccessful. They do, however, illustrate the broad intent and scope of IBM's response to its loss of effective control over the PC, a response that changed the character of its relations with Intel, as well as with other firms like Microsoft.

aggressively in the network chip (NPU) segment, along with Motorola. Both firms had been anticipating the growth of this market segment: in 1999, IBM had formed a strategic alliance with network equipment leader Cisco Systems, while Intel acquired Netboost, a network services tools supplier, as part of its bid to get into the networking chip market. In the telecommunications chip market, Intel had a much stronger position than IBM. By the year 2000, Intel had signed long-term contracts with some of the cellphone industry's biggest players (e.g. Ericsson) that brought it a big share of the market. AMD meanwhile signed a $400 million supply agreement with Samsung.

Opportunities also began to emerge for new semiconductor applications in consumer electronics. In 2003, IBM joined Sony and Toshiba to create a video game chip, the Cell Processor, for the Sony PlayStation3. While IBM was willing to adapt its technology to satisfy the needs of consumer-product firms, Intel struggled with the short life-cycles and constant redesigns needed in this industry. As a result, Intel did not appear in Dataquest's 2003 rankings of the top 20 consumer chip makers, even though it tried a number of times to launch consumer product-oriented chips and systems. In 2005, IBM won further contracts with two other major consumer electronics products, Nintendo and Microsoft. The latter was a blow to Intel, for Microsoft had long been a strong ally of Intel's in both the personal computer market as well as for the Xbox. Quite recently, Apple and switched to using Intel chips instead of the PowerPC (a joint project of IBM and Motorola), and so the competitive battle continues.

While they competed aggressively, from the late 1990s Intel and IBM also began cooperating in several areas. Around 1998, they began joint development work on Unix along with SCO. Then, around 2002, Intel and IBM, began collaborating on the development of highly compact and efficient computer servers known as "blade servers". A key feature of IBM's blade servers is that they are based on Linux software and utilize Intel microprocessors. The degree of commitment to Intel is underscored by IBM's Vice President of Linux Servers, who is reported to have said in 2002 that "we were in this game early, and we've benefited by working very closely with Intel. In fact, we've substantially contributed to optimizing Linux on the 64-bit Intel architecture. And we're leveraging IBM research and the many technologies that we've developed over the years, and applying them in the Intel server space to give customers compelling reasons to prefer IBM's Intel solutions".[6] Interestingly,

[6] "Linux on Intel: A Battle IBM Will Win", June 2002. Available from http://www-03.ibm.com/linux/news/michos.shtml.

cooperation between Intel and IBM occurred not in the semiconductor space where they are direct rivals, but in complementary areas such as software and server applications.

Starting in the late 1990s, IBM also stepped up the degree to which it collaborated with AMD. During the late 1990s to the early 2000s, IBM announced a series of innovations intended to define the future direction of semiconductor technology: Silicon on Insulator (SOI) technology, copper interconnects on chips, electron beam lithography, and double gate transistors. As part of this trajectory, in 2001 IBM officially ended its technology agreement with Intel, and instead signed a 10-year agreement with AMD to jointly develop high-end semiconductor manufacturing technology. To date, IBM and AMD have developed 65-nanometer and 45-nanometer process technologies for 300-mm semiconductor wafers, as well as other techniques to improve microprocessor speed and power efficiency.

Since the turn of the century, IBM has also started to cooperate with both Intel and AMD (along with other partners) to promote Linux and other open source software innovations. It has shifted its strategy towards being more of a service and solution provider, and away from being a hardware vendor. From 1997 to 2004, IBM acquired more than ten software companies, three data management companies, and four E-Service companies. This included the $3.5 billion purchase of PwC Consulting, which had strengths in "planning and installing high-end software for corporate accounting, dealing with customers, and managing corporate supplies".[7]

To summarize, in the early 1980s, Intel cooperated with IBM as a vendor of microprocessor chips, an important component in the IBM PC. At that time it was a system designed and controlled by IBM. By the 1990s, Intel (along with Microsoft) had usurped control of the PC architecture, and had become more profitable and more powerful in the PC market than its initial benefactor and customer, IBM. This led to a period of attrition during the 1990s between Intel and IBM. IBM began teaming up with other chip vendors – including AMD – and successfully disengaging itself from Intel. In the 2000s, IBM withdrew from the PC market and re-focused on its mainframe business, semiconductor R&D, and new downstream applications. Meanwhile, Intel had built up its own R&D strength throughout the 1990s, and by 2000 was beginning to compete with IBM in applying semiconductor technology to consumer electronics and computer networking. While they remained highly competitive, Intel and IBM began to

[7] c|net News, 30 July 2002.

collaborate on blade servers and Unix and Linux systems. These patterns are reflected in Figure 1. We can see a shift from cooperation during the early 1980s to competition between IBM and Intel thereafter. We also observe that around the turn of the century, IBM and Intel began to cooperate in some areas while remaining rivals in the core semiconductor business.

AMD's relationship with the other two firms is easier to characterize. With Intel, it was consistently a direct rival, except for an early truce imposed by IBM through the second-sourcing agreement between AMD and Intel. Over time, Intel has faced increasingly intensive competitive pressure from AMD, as the latter has expanded its customer base among sellers of personal computers and leveraged on IBM's strength as a process technology partner. In contrast to Intel, AMD's relationship with IBM (Figure 2) shows an initial period of cooperation, followed by a period during which there were no major competitive or cooperative events in the 1980s and early 1990s (a stark contrast to Figure 1 during this period), and finally a period of renewed interest in the late 1990s, when IBM began collaborating again with AMD.

In the following section, we investigate how these events relate to the patenting behavior of the three firms. Do changes in the level of cooperation and competition have an effect on the patenting intensity at these firms? And is there a corresponding change in the patterns of knowledge flow among the three firms over time?

4. Patent Analysis

We identified all US patents awarded to IBM, Intel and AMD between 1976 and 2004. Patent data has been used as a proxy for innovation in many studies (e.g., Ahuja and Katila, 2001, Hall and Ziedonis, 2001), while patent citation data has be used to trace knowledge flows (e.g. Jaffe et al., 1993, Rosenkopf and Almeida, 2003). Using patent citations for this purpose has many deficiencies. It does not capture the organizational knowledge gained from "learning by doing" (Rosenberg, 1982) or the organizational capital created on the shop floor (Lazonick, 1990). Moreover, patent citations originate not just from the inventor(s), but also from patent counsels at the firm and from the reviewing patent examiner (Cockburn et al., 2002). Nonetheless, patent citation analyses have offsetting virtues. They are externally observable, not subject to retrospective recall bias, and can be adjusted in various ways to reflect differences in the importance of respective patents (Jaffe et al., 1993).

We take a novel approach of dividing these patents into four categories, or "Patent Bins". This allows us to identify areas that are directly relevant to semiconductor technology in which the firms are likely to compete head-on, as opposed to those that are upstream or downstream where they may have greater opportunities to cooperate. Our classification is based on each patent's Patent Class (as defined by the US Patent and Trademark Office), and we rely upon the knowledge of two authors of this paper who are familiar with semiconductor technology to assign each patent class into one of four patent bins.[8] The four patent bins are:

- Competitive: contains patents that are directly relevant to semiconductor design and processing. This includes the two main US patent classes relating to semiconductors: 438 (semiconductor manufacturing) and 257 (active solid state devices).

- Downstream: contains patents that make use of semiconductors, such as those in US Patent class 343 (computer graphics hardware) and 707 (databases).

- Upstream: contains patents for technologies that help semiconductor companies to build better chips. This includes better chemistry, coating processes, printing techniques (used for photolithography), etc.

- Unrelated: contains patents that don't fall into the above categories. Examples here include surgery, education, and distillation.

Table 1 contains a detailed breakdown of the patent classes categorized in each bin. Table 2 shows the number of patents assigned to IBM, Intel and AMD in each bin. IBM has a larger number of patents, reflecting its much larger size. However, IBM has a smaller proportion of patents in the competitive bin as compared to the other two firms, reflecting its IBM greater degree of diversification into upstream semiconductor manufacturing processes, downstream applications, and unrelated areas. In contrast, a majority of Intel's and AMD's patents are in the competitive bin due to their narrower business scope. In order to provide some objective validation of our classification scheme, we identified the top eight patent classes in which Intel obtained patents.

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[8] One may be concerned about the reliability of these classifications, in particular that upstream or downstream patents may have been misclassified into competitive bins, therefore biasing the results. While this is a possibility, industry participants who have been shown our classification scheme (Table 1) consider it reasonable. And the patenting trends we find in Figure 4 and describe below are consistent with the overall strategic shifts of these companies as reported in the press, i.e., IBM moving increasingly towards services, Intel expanding downstream, and AMD remained mainly focused on semiconductors.

They all fall into the competitive bin, which is reassuring given that Intel is very tightly focused on the semiconductor industry as compared to IBM.

[Tables 1 and 2 about here]

4.1 Competition, Cooperation and Patenting Frequency

Figure 4 contains a breakdown, by year, of the number of patents per bin awarded to IBM, Intel and AMD. The decline in total patents in the final 3 years is due to right-censoring because a number of patents would have been applied for that were not yet granted. Figure 4 shows that the three firms have very different patent portfolios, reflecting their widely different size and scope. IBM obtained a much larger number of patents per year than Intel and AMD, even if we only look within the competitive bin. Moreover, IBM has a larger number of patents outside the competitive bin than the two smaller rivals, reflecting its broader scale of operations.

In recent years, IBM has moved increasingly towards patenting downstream inventions. This is consistent with the shift in its strategy towards a greater emphasis on downstream applications and services, as reported in the previous section. Figure 4 also shows that Intel has followed suit in expanding its portfolio of downstream patents, but to a lesser degree than IBM. Meanwhile AMD has remained largely focused on patenting within the competitive bin during this time period. By 2004, only about 34% of IBM's patents were in the competitive bin, with the corresponding percentages being 57% for Intel and 73% for AMD.

[Figure 4 about here]

We now turn to the propensity of Intel and AMD to patent relative to IBM (Figure 5). We use IBM as the baseline for comparison because it is the largest of the 3 firms, and it was the incumbent firm. The qualitative evidence in the previous section of the paper would lead us to predict that Intel's patenting behavior should differ substantially from that of IBM. Figure 5 shows that beginning in the late 1980s, Intel patents as a fraction of IBM's patents increased dramatically, especially in the competitive bin. For the competitive patent bin, Intel's patents as a fraction of IBM's grows from around 20% in 1990 to 50% in 1999 and to 70% in 2004. Additional analysis shows it is driven by rapid increases in patenting within patent classes that are easily seen as being relevant to semiconductors: US classes 257 (active solid state devices), 438 (semiconductor device manufacturing), 711 (memory) and 327 (nonlinear devices). This rapid increase offers is suggestive of an attempt by Intel to catch up with IBM, since by construction these patents lie in directly competitive technology areas. For the upstream bin, the ratio increases from 20% in 2001 all the way up to 70% in 2004. This is consistent with our qualitative analysis that by the late 1990s, Intel had grown strong enough to wean itself from IBM.

[Figure 5 about here]

In contrast to the competitive patents, Intel's growth in upstream patents relative to IBM is modest until around 2002. This too is reflective of their difference in strategy, with IBM investing more heavier in upstream science while Intel relying to a greater degree on external sources for fundamental research. In the downstream and unrelated categories, Intel's patents begin to rise as a proportion of IBM's patents in the last 1990s. This reflects the growing scope of Intel's business and is consistent with a co-specialized behavior in downstream market of applications that utilize semiconductors, which echoes our qualitative findings in the previous section. Nonetheless, it is surprising that the growth in Intel's downstream patents has been modest even from the late 1990s, especially given the observed cooperation emerging around that time. One possible explanation is that the cooperation between Intel and IBM occurred mainly in the software area (e.g. linux for blade servers), that until recently were not patentable.

For AMD, we expect a different pattern of patenting behavior relative to IBM, reflecting high levels of cooperation in the early 1980s and again from around 2000. Consistent with this, the lower part of Figure 5 shows a sharp decline in AMD competitive patents as a proportion of IBM's starting around 2000. Around the same time, AMD's proportion of upstream and unrelated patents begins to increase, possibly reflecting the higher level of co-specialization. But as with Intel's patents, we see a surprising absence of AMD patents in the downstream area during both periods of cooperation, i.e. in the early 1980s and from the late 1990s onwards. Another surprise is the presence of a peak in the number of competitive patents relative to IBM around 1987-1989. We suspect this is a byproduct of the competitive dynamics between AMD and Intel: it was around 1987 that Intel discontinued their second-sourcing agreement with AMD, so AMD had to intensify R&D in its core semiconductor area in order to survive.

4.2 Patent Citations and Knowledge Interdependence

To explore the pattern of knowledge flows, we turn to an analysis of patent citations. Between 1976 and 2004, IBM's US patents made 391,857 "backward citations", which are defined as citations to other US patents. During the same period, Intel's patents made 95,135 backward citations and AMD's made 72,310 backward citations. On a per-patent basis, this works out on average to around 10.2 backward citations/patent for IBM and 10.3 backward citations/patent for Intel, and around 9.4 backward citations/patent for AMD. Thus, Intel's and IBM's patents have similar propensities to cite other patents, and at a greater rate than for AMD. The number of backward citations per patent over time has steadily grown from around 4.8 citations per patent in 1976 to around 11.6 in 2004. This suggests that semiconductor technology has become more complex and cumulative as it matured over the past two decades (Brusoni et al., 2001).

We also calculated the number of forward citations to each firm's patents, which is calculated as the number of citations made by other US patents to the focal patent. This is a measure of technological impact (Hall et al., 2005). Between 1976 and 2004, IBM's patents received 408,585 forward citations, whereas Intel's patents received 69,853 forward citations and AMD's patents received 51,285 forward citations. On a per-patent basis, IBM received 10.6 forward citations per patent, with the corresponding figure being 7.6 for Intel and 6.6 for AMD. This suggests that IBM's patents have on average significantly higher impact than Intel's and AMD's.

Patent citation analysis shows that all three firms relied a great deal upon external sources of knowledge. For each firm, we created an index of self-citation, which is the number of citations a firm makes to its own patents as a fraction of the total number of citations made by that firm's patents. For example, suppose that Intel's patents made ten citations in year 1970, of which 3 were to Intel's own patents and 7 were to patents of other organizations. Then, Intel's self-citation index for 1970 would be 0.3. Firms with higher self-citations are more self-reliant, and less dependent on other organizations for technology.

We find that self-citations are low relative to overall citations. IBM's self-citation ratio is 21.7% for competitive patents, 21.7% for downstream patents, and 15.8 % for upstream patents. The self-citation indices for Intel are 14.7%, 7.5% and 9.1% respectively, and for AMD they are 15.6%, 12.7% and 7.7%. As one might expect, IBM has a higher level of self-reliance than Intel or AMD across all three categories. But for all three firms (including IBM) the self-citation rate is low across patent bins, implying that each firm relied heavily on external sources of knowledge.

Further analysis reveals another interesting fact: the firms depended upon a surprisingly broad range of external sources for technical knowledge. Many of the backward citations made by Intel and IBM are not to the top semiconductor firms. Out of IBM's backward citations, only 20.0% are made to its own patents. Of the remainder, 28.6% are to the other top-19 firms, 6.5% are to universities, institutes and US government respectively, 8.9% are to pre-1976 patents (for which data is not easily available electronically), and 36% are to other organizations. As for Intel's backward citations, 11.6% are to its own patents, 41.7% are to the other top-19 firms that it cites, 1% are to US Government patents, 8.8% are to universities, institutes and US government, 3.2% are to pre-1976 patents, and 33.7% are to other organizations. What stands out in both cases is that a large fraction of all patent citations are to organizations other than the top 20 firms cited. We are currently analyzing the composition of these "others" and will report on them in the future. Regardless of outcome, the results point to a broad and diversified knowledge base that both firms apparently rely upon. Preliminary analysis shows that Intel's patents make citations to those patents owned by roughly 300 separate organizations; IBM's patents make citations to twice as many organizations. Given IBM's dominant position in this market and its oft-mentioned patent arsenal, the breadth of the knowledge base that IBM and Intel depended upon is surprising. It questions the assumption that IBM (or any other firm) had a stranglehold on the valuable knowledge in this industry, and suggests that perhaps an open rather than closed model of innovation might have been appropriate.

Apart from asking how heavily each firm depends upon external sources of knowledge, an even more intriguing question is the extent to which each relies upon the other. To assess the pattern of interaction between Intel and IBM, we created an indexed measure of cross-citation. This measure consists of the number of citations to the other company's patents, relative to the number of citations of the firm's own patents. So, for IBM it would be the number of citations to Intel's patents divided by the number of citations to its own patents. We use self-citations in the denominator to adjust for the fact that IBM has many more patents than Intel has.

Cross-citation indices are charted in Figure 6. A huge asymmetry exists. The citations made by IBM's patents to those owned by Intel are only 6.9% of self-citations, and the citations by IBM to AMD's patents are only 4.4% of self-citations. In contrast, Intel's patent citations to IBM patents are 73.5% of its self-citations. For AMD, the corresponding figure (citations to IBM patents as a percentage of self-citations) is 49.8%. The difference is of an order of magnitude, and exists across all patent bins. This result provides some support for the proposition that Intel and AMD relied a great deal upon IBM's research, even though they were competitors. Apart from this, Figure 6 also shows that the degree to which Intel and AMD cited each others' patents is low relative to self-citations (Intel's citations to AMD are 17% of its self-citations, while AMD's citations to Intel are 28% of its self-citations). Indeed, the middle and bottom charts in Figure 6 suggest that both AMD and Intel depended upon IBM for knowledge flows much more than each other. So, while AMD and Intel produce similar products and although AMD had once licensed technology from Intel as a second-source manufacturer, we find that the knowledge flows between them are surprisingly low, and that both firms depend mainly upon IBM a more than they do each other.

[Figure 6 about here]

Our analysis in Section 3 shows that IBM and Intel had a cooperative relationship till around 1986, then entered a period of competition till the late 1990s, and began a period of co-opetition around 1999. AMD and IBM were especially cooperative in the early 1980s and then again starting in the late 1990s; AMD and Intel remained rivals throughout. We therefore split our analysis into three different time periods to see if the pattern of knowledge dependence may have changed as the relationship among these firms evolved. These time periods are: 1985 and earlier, 1986-1999, and 1999-onwards. We find that IBM's citations to Intel as a percentage of self-citations rose from 3% in the first period, to 5% in the second period, and 9% in the third period. Thus, IBM's patents did indeed cite Intel's patents more over time (in relation to its own self-citations). This is not surprising, since Intel's patents grew at a faster rate than IBM's, and Intel's R&D spending in semiconductors overtook IBM's by the end of the decade. Yet, the 9% statistic in the third period shows that IBM continued to be largely self-reliant. A similar story emerges with AMD: the cross-citation rate by IBM's patents to AMD patents grew from zero in the first period to 3% in the second period and reached 5% in the third period. While there is an upward trend, IBM's dependence upon AMD remains low even after 1998 when they began to cooperate again.

Intel was the technological follower in the beginning of our analysis, so it is interesting to compare its cross-citation ratio across time. Intel's cross-citations to IBM patents grew slightly from 0.77 in the first period (pre-1986) to reach 0.90 in the second period (1986-1998), and declined to 0.69 after 1999. It is interesting that despite the shift from cooperation to competition around 1986, Intel's knowledge dependence upon IBM actually *increased* somewhat, before subsiding. Intel continued to rely heavily upon IBM in relation to itself, citing 0.90 of IBM's patents for every self-citation during 1986-1998, and 0.69 IBM patents for every self-citation thereafter. In fact, even after 1999, Intel's patents remain seven times more likely to cite IBM's patents than IBM's patents are to cite Intel's patents. In additional analysis, we find that Intel's dependence on IBM is even higher in the downstream and upstream patents. In those areas, Intel's patents are 20 to 30 times more likely to cite IBM's patents, than IBM's patents are to cite Intel's patents. Unlike with IBM, Intel's dependence upon AMD increases slightly over time, but remains low throughout.

We also observe surprises in AMD's cross-citations over time. While AMD's heavy knowledge dependence upon IBM before 1986 is unsurprising given their cooperation then, we also observe that AMD's cross-citation rates declining in *both* subsequent periods. Thus, even though AMD and IBM began to collaborate intensively again in the late 1990s, AMD continued to reduce its dependence on IBM in that period. In fact, AMD's cross-citation rate with IBM in the post-1998 period is 0.43, which is even less than Intel's cross-citation rate with IBM of 0.69 during the same time period. AMD also reduced its knowledge dependence upon Intel, with its cross-citation rate to Intel patents declining from 0.50 in the first two periods to 0.25 after 1998.

In summary, we find that IBM, Intel and AMD depended heavily on external sources of knowledge. Intel and AMD depended upon IBM a great deal more than IBM depended upon either of those firms. Both Intel and AMD depended upon one another relatively little. Although Intel and IBM moved from an environment of cooperation in the 1980s to one of competition in the 1990s and to a regime of co-opetition thereafter, there doesn't seem to have been a corresponding shift in their patterns of knowledge dependence. IBM remains more self-reliant, while Intel continues to rely heavily upon IBM patents. AMD reduced its knowledge dependence upon IBM over time, even though they began cooperating in the late 1990s.

5. Discussion

Given the 28-year timeframe of our study, and the many events that occurred during this period, we report a wealth of observations. It seems clear that patenting behavior within the "competitive bin" is generally consistent with changes in the intensity of competition between the three firms. This leads us to our first proposition, that the more competitive two companies are towards each other in the product market, the less they are able to cooperate in those technologies, and therefore the more likely they are to obtain patents in competitive areas (or bins).

A second observation is that of a strong asymmetry between IBM and its smaller rivals. Intel behaves initially very much like a free-rider (with very few patents of its own), then later intensifies its own competitive patenting behavior, and now is shifting to a more balanced pattern of patenting across its value chain. IBM behaves like a first mover in the beginning of the study, and continues to lead the industry in the amount and scope of its patenting through the end of our study. Given the shift in sales among the two firms, IBM's persistence in its R&D is striking.

Cross-citation rates also reveal interesting contrasts. Even through periods of intense competition, Intel continued to have high knowledge dependence on IBM, as evidenced by its continued high degree of cross-citation to IBM, which is *not* reciprocated by IBM (Figure 6). IBM's cross-citation to Intel patents remains significantly lower throughout the period of the study. AMD, by contrast, cited IBM patents heavily in the early periods of the study, but at a declining rate towards the end of the study.

We therefore arrive at a second proposition: despite changes in downstream competition and cooperation in the product market, small firms may remain dependent upon larger ones in the technological arena over long periods of time. Notice the subtle distinction between our first proposition, which concerns rates of patenting, versus our second proposition, which concerns rates of citation. Under the open innovation paradigm, firms re-position to focus on areas of strength along the value chain. This specialization implies that Intel and AMD will tend to cite IBM's upstream and downstream patents more than IBM is likely to cite their core semiconductor patents. Thus, even as Intel and AMD begin to patent aggressively in competitive areas (Proposition 1), their citations to IBM patents is undiminished (Proposition 2).

An intriguing finding is the large and persistent role of "Other" in the citation behavior of all of three firms, but most especially IBM. While IBM utilizes self-citations far more than Intel or AMD, IBM's leadership R&D strategy also causes it to make extensive citations to knowledge sources that are far distant from the leading firms in the semiconductor industry. Casual inspection reveals that organization such as universities, research institutes, small and medium sized firms, and individuals are all represented in this "Other" category of knowledge sources. This is not something emphasized by traditional economic views of R&D competition. It is, however, quite consistent with the open innovation emphasis on the importance of external knowledge sources.

> "In Open Innovation, useful knowledge is generally believed to be widely distributed, and of generally high quality. Even the most capable and sophisticated R&D organizations need to be well connected to these external sources of knowledge." - Chesbrough (2006), pg. 9

There are some results that we do not fully understand. Somewhat surprisingly, patenting upstream and downstream along the value chain is only partially related to changes in competitiveness. We see a consistent pattern for Intel in the late 1990s and AMD at the turn of the century, but there are also periods for which patenting in upstream and downstream areas was not as intense as expected. One likely explanation is that many other factors play a role in a firm's R&D and patenting decisions. For example, although Intel and IBM began to cooperate downstream from the late 1990s, this includes areas such as software that were not patentable till recently. It may also be that patenting activity has sufficiently long lags that our approach cannot discern these expected shifts with adequate precision. Equally, it may be that firm rivalry changes more rapidly than does firm R&D strategic capabilities.

6. Conclusions and Implications

We present a "quantitative case study" of IBM, Intel and AMD's patenting behavior across a 28-year period. The patterns of competition and cooperation, and of the resulting patenting activity by these firms, is unusually rich.

Our case study offers some interesting puzzles to scholars of technological R&D. IBM was clearly a technology pioneer in the semiconductor industry, and sustained an enormous investment in both basic and applied research in the field over many decades. In this sense, they were a Chandlerian first mover (Chandler, 1990): a highly capable firm that exploited economies of scale and scope by investing in new technologies, marketing, management and a broad range of other areas. Yet, as we have shown, this did not prevent Intel and AMD from succeeding in the product market. Thus, traditional conceptions of R&D strategy, which are based on an assumption of tight coupling between firm R&D and firm strategy, are not applicable in this case. The choice of "compete or cooperate" is too reductive. Additional choices such as co-specialization, cross-licensing and technological cooperation are viable when sources of industrial knowledge are loosely coupled.

One implication for managers is that it is possible for small firms to compete in the product market while co-opetiting in the market for technology. Managers should be aware that they can actively leverage the stream of open innovation outside their firm (even from the leading rival), while trying to develop their own internal R&D capabilities. In this respect, Intel and AMD provide valuable cases to legitimize such a strategy.

Intel overtook IBM not by outspending IBM in the knowledge market. Intel passed IBM in sales long before the crossover point in R&D was reached, and only in 2006 did Intel's expenditure on R&D begin to exceed that of IBM's. Instead, Intel pursued a different, more open approach to R&D. Given the widening spread of useful knowledge in the semiconductor industry (recall how many patents were not owned by any of the top 15 firms in the industry), one lesson is to engage in more open innovation strategies in such circumstances.

AMD remains the focused upstart, leveraging IBM heavily in the early years, and less so more recently. Throughout the period, even when allied to IBM, IBM finds AMD's patents to be of relatively less interest even than those of Intel. Given that the tradeoffs between value creation and value capture (Simcoe, 2006) are different across large and small firms, we believe that exploring these and other asymmetries will lead to fruitful outcomes in the development of research on open innovation.

But what about the pioneer in an open innovation world? With the considerable benefit of hindsight, it seems clear that IBM stuck with a deeply vertically integrated strategy in semiconductors for too long. Being too closed in an increasingly open semiconductor industry cost IBM dearly. We see here the limits to the Chandlerian firm. By the mid 1990s, it was in deep financial trouble, and its new CEO, Lou Gerstner, cut around $2 billion from the $5.1 billion annual R&D budget (Buderi, 1999). In 1996, a new Research Director was installed, and he changed the division's mission from "famous for its science and technology and vital to IBM" to just "vital to IBM's future success" (Buderi, 2000). A major reorganization of every aspect of IBM's research division ensued over the coming years, and IBM has begun to pursue a more open approach. However, it has taken a decade for it to fully embrace the new approach.[9]

So what could IBM have done differently? We speculate that there were actions open to IBM in both the knowledge market and the product market that would have helped it do better than it did. One strategy in the product market would have been to utilize more open markets for capital-intensive portions of the semiconductor business. For decades, IBM restricted the output of its semiconductor plants to itself. Letting others buy IBM's chips earlier would have given IBM a larger market share in chips beyond its own use, and would have spread the high fixed costs of semiconductor development and manufacturing over a larger base of volume.

Another strategy would have been to compete and cooperate in the knowledge market (co-opetition, in Brandenburger and Nalebuff's terms) by licensing out more of its advanced technology much earlier, even as it used that technology in its own products. Again, this would have spread the fixed costs of R&D more widely. In addition, greater licensing may have helped IBM to establish de facto standards in key technologies, and created technological platforms that other companies would have been more likely to follow. In turn, this would have helped IBM sustain its technological lead, supported by a group of "happy followers" in the rest of the industry.

A third option in the product market would have been to foster the development of spin-off companies employing IBM technologies in markets that were too small (at least initially) to be of interest to IBM, but might have subsequently grown more valuable. Retaining a minority equity stake in these spinoffs (perhaps in return for use of IBM's intellectual property) would have offered IBM greater insight into emerging market opportunities, along with an option to repurchase promising ventures if and when they became strategically important to IBM. This is a method of acknowledging that markets often do a better job of finding valuable opportunities to commercialize nascent technologies than internal planning processes.

A final option in the knowledge market would have been to imitate aspects of Intel's and AMD's approach, by relinquish long term investment in advanced semiconductor R&D, and seeking to create alternative ways to access work done elsewhere. IBM's deteriorating financial performance also suggests that it should have

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[9] For recent reports on IBM's move towards a more open approach, see "The new face of R&D: What's cooking at IBM, HP and Microsoft", Computerworld, 10 July 2008, and "Big Firms Eye Open Innovation for Ideas", npr.org, 27 May 2007

attempted to appropriate a larger share of the surplus it created. Ultimately, if the pioneering firm cannot appropriate enough of the gains from its R&D investments, it cannot sustain them (Teece, 1986). Who then would perform the basic research needed for semiconductors? Universities, research consortia, research institutes, suppliers, and others would have to step up to fill this void. Are there ways to ensure that these alternative investments would have been adequate? And would a different stance by IBM towards Intel, AMD and other players have been credible? These are important questions, and ones we hope future research will address.

In further analysis, we hope to unpack the "other" citations, to develop a more systematic understanding of the role these diverse knowledge sources play in the R&D strategies of semiconductor firms. The paper also raises questions about how technological licensing among the three firms might have shaped competition the product market. And clearly, our study involves only three firms in a single industry. Much more work will be needed to clarify how knowledge flows relate to open innovation processes in different industries and institutional environments.

We also hope that future work will take up on our approach of analyzing the heterogeneity within each firm's technological portfolio. We show that firms behave quite differently in upstream, downstream and competitive areas in relation to open innovation. This raises interesting questions, such as which portions of its technological portfolio should a firm maintain as proprietary, and which ones should it open up? How does relative stability (i.e., the rate of change) in product markets and technological markets affect these decisions? Underlying these questions is a central issue that remains unresolved: how can an incumbent firm develop a successful open innovation strategy, one that involves managing a complex set of relationships and conflicts among myriad partners in both technology and product markets, and how can it do so profitably while nimble entrants with different capabilities threaten to erode the its market share despite depending upon the same technological base?

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Table 1: US Patent Classes in each Patent Bins

Patent Bin	Competitive (All)	Downstream	Upstream	Unrelated
US Patent Classes in this bin	438 SEMICON DEVICE MFG: PROCESS 257 ACTIVE SOLID-STATE DEVICES (E.G., TRANSISTORS, SOLID-STATE DIODES) 714 ELECT COMPUTERS & DIGITAL PROCESSING SYSTEMS: ERROR DETECTION/ CORRECTION & FAULT DETECTION/ RECOVERY 711 ELECT COMPUTERS & DIGITAL PROCESSING SYSTEMS: MEMORY 710 ELECT COMPUTERS & DIGITAL DATA PROCESSING SYSTEMS: INPUT/ OUTPUT 365 STATIC INFORMATION STORAGE & RETRIEVAL 712 ELECT COMPUTERS & DIGITAL DATA PROCESSING SYSTEMS: PROCESSING ARCHITECTURES & INSTRUCTION PROCESSING (E.G. PROCESSORS) 713 ELECT COMPUTERS & DIGITAL PROCESSING SYSTEMS: SUPPORT 327 MISC ACTIVE ELECT NONLINEAR DEVICES, CIRCUITS, & SYSTEMS 326 ELECTRONIC DIGITAL LOGIC CIRCUITRY 708 ELECT COMPUTERS: ARITHMETIC PROCESSING & CALCULATING 380 CRYPTOGRAPHY 377 ELECT PULSE COUNTERS, PULSE DIVIDERS, OR SHIFT REGISTERS: CIRCUITS & SYSTEMS	**Top 10:** 345 COMPUTER GRAPHICS PROCESSING, OPERATOR INTERFACE PROCESSING, & SELECTIVE VISUAL DISPLAY SYSTEMS 360 DYNAMIC MAGNETIC INFORMA-TION STORAGE OR RETRIEVAL 707 DATA PROCESSING: DATABASE & FILE MANAGEMENT, DATA STRUCTURES, OR DOCUMENT PROCESSING 709 ELECT COMPUTERS & DIGITAL PROCESSING SYSTEMS: MULTIPLE COMPUTER OR PROCESS COORDINATING 395 INFORMATION PROCESSING SYSTEM ORGANIZATION 370 MULTIPLEX COMMUNICATIONS 382 IMAGE ANALYSIS 369 DYNAMIC INFORMATION STORAGE OR RETRIEVAL 341 CODED DATA GENERATION OR CONVERSION 704 DATA PROCESSING: SPEECH SIGNAL PROCESSING, LINGUISTICS, LANGUAGE TRANSLATION, & AUDIO COMPRESSION/ DECOMPRESSION **Others:** 375, 358, 348, 340, 705, 706, 700, 379, 349, 702, 455, 333, 178, 200, 381, 343, 342, 701, 386, 353, 429, 463, 332, 364, 101, 273	**Top 10:** 361 ELECTRICITY: ELECT SYSTEMS & DEVICES 430 RADIATION IMAGERY CHEMISTRY: PROCESS, COMPOSITION, OR PRODUCT THEREOF 324 ELECTRICITY: MEASURING & TESTING 427 COATING PROCESSES 29 METAL WORKING 216 ETCHING A SUBSTRATE: PROCESSES 359 OPTICS: SYSTEMS (INCLUDING COMMUNICATION) & ELEMENTS 347 INCREMENTAL PRINTING OF SYMBOLIC INFORMATION 439 ELECT CONNECTORS 356 OPTICS: MEASURING & TESTING **Others:** 228, 156, 174, 399, 385, 205, 204, 219, 331, 235, 73, 363, 134, 372, 313, 165, 451, 118, 323, 414, 117, 252, 148, 264, 330, 505, 307, 242, 528, 525, 106, 432, 226, 378, 83, 501, 524, 62, 374, 445, 206, 420, 419, 425, 338, 523, 336, 522, 210, 406, 494, 15, 34, 423, 141, 209, 510, 239, 270, 368, 388, 408, 556, 33, 417, 51, 329, 415, 521, 526, 549, 55, 137, 367, 534, 540, 376, 392, 502, 546, 568, 588, 95, 96, 508, 548, 560, 562, 564, 570.	**Top 12:** 400 TYPEWRITING MACHINES 428 STOCK MATERIAL OR MISC ARTICLES 250 RADIANT ENERGY 271 SHEET FEEDING OR DELIVERING 318 ELECTRICITY: MOTIVE POWER SYSTEMS 315 ELECTRIC LAMP & DISCHARGE DEVICES: SYSTEMS 355 PHOTOCOPYING 310 ELECT GENERATOR OR MOTOR STRUCTURE 346 RECORDERS 335 ELECTRICITY: MAGNETICALLY OPERATED SWITCHES, MAGNETS, & ELECTROMAGNETS 248 SUPPORTS 384 BEARINGS **Others**: 312, 84, 269, 442, 198, 320, 600, 294, 606, 65, 136, 422, 434, 436, 225, 1, 116, 396, 53, 74, 109, 126, 128, 222, 227, 236, 403, 454, 493, 100, 16, 192, 221, 277, 279, 292, 362, 52, 140, 184, 188, 211, 220, 234, 283, 366, 40, 409, 433, 435, 474, 492, 60, 604, 623, 70, 72, 75, 81, 108, 138, 164, 172, 173, 181, 191, 193, 229, 232, 241, 254, 266, 267, 280, 285, 337, 373, 4, 411, 424, 431, 601, 607, 716, 91, 92, 102, 122, 125, 132, 177, 182, 186, 194, 202, 23, 24, 246, 290, 297, 298, 30, 352, 36, 37, 404, 405, 416, 43, 47, 473, 483, 558, 57, 585, 7, 89.

Notes: The top patent classes in each bin are the ones for which IBM has the highest number of patents.
All US patent classes in which either IBM or Intel received a patent are listed.

Table 2: Number of patents in each patent bin (1976-2004)

Patent Bin	IBM patents	Intel patents	AMD patents
Competitive	12943 (33.6%)	5223 (56.7%)	5607 (72.5%)
Downstream	14856 (38.5%)	2245 (24.4%)	955 (12.4%)
Upstream	8034 (20.9%)	1487 (16.1%)	934 (12.1%)
Unrelated	2699 (7.0%)	253 (2.8%)	237 (3.0%)
TOTALS	**38532**	**9208**	**7733**

Figure 1: Chronology of Key Events: IBM and Intel

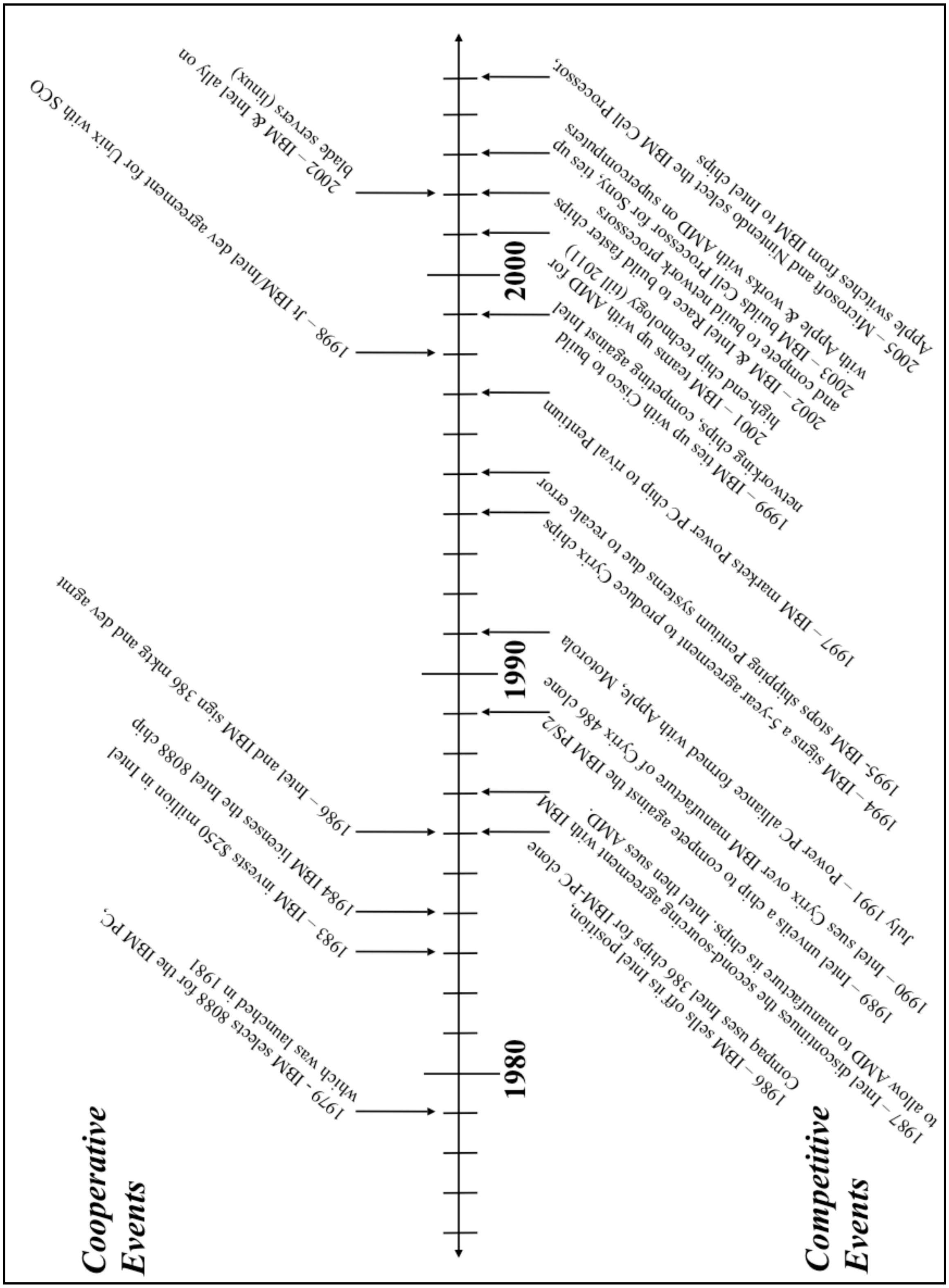

Figure 2: Chronology of Key Events: IBM and AMD

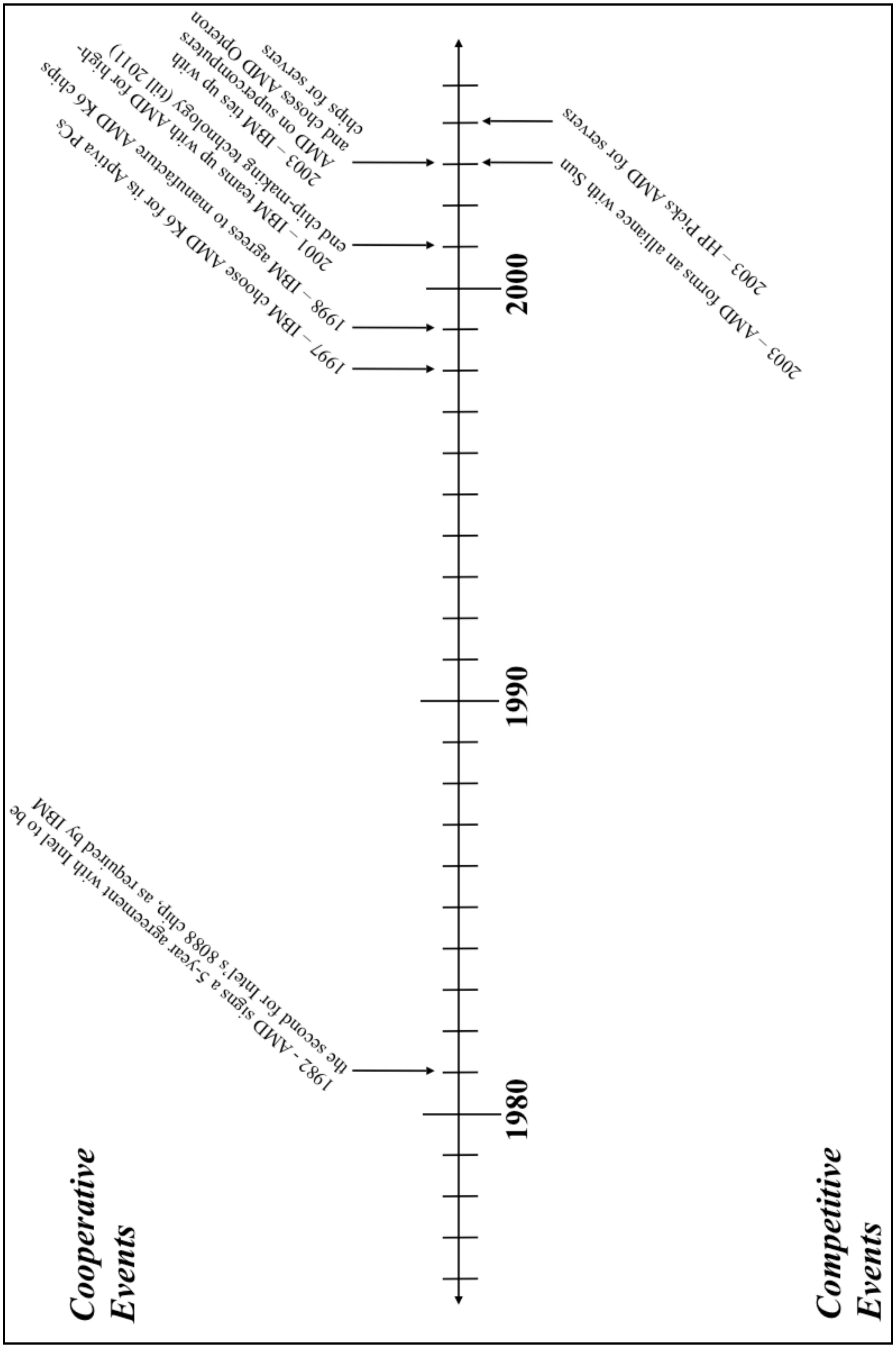

Figure 3: R&D expenditure of IBM, Intel and AMD

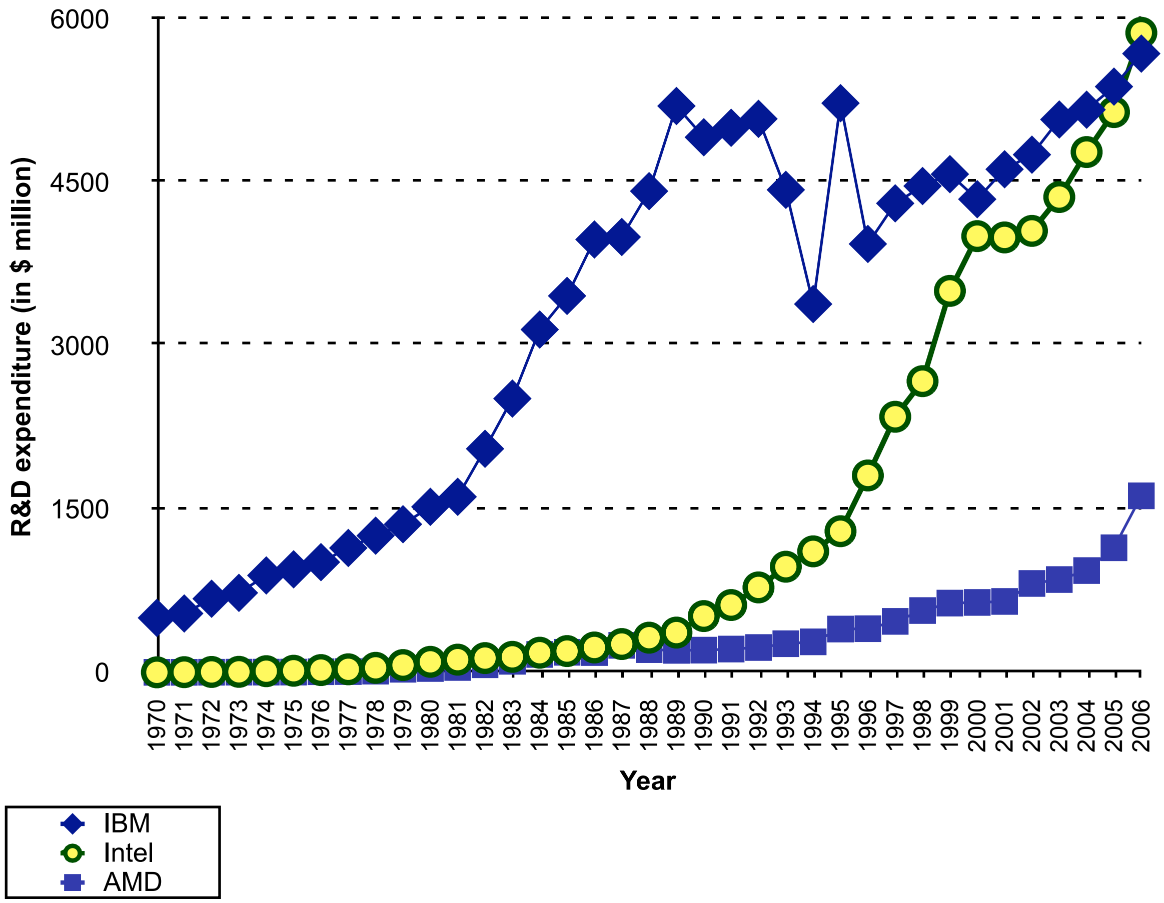

Figure 4: Patents Per Bin: IBM (top), Intel (Middle) and AMD (Bottom)

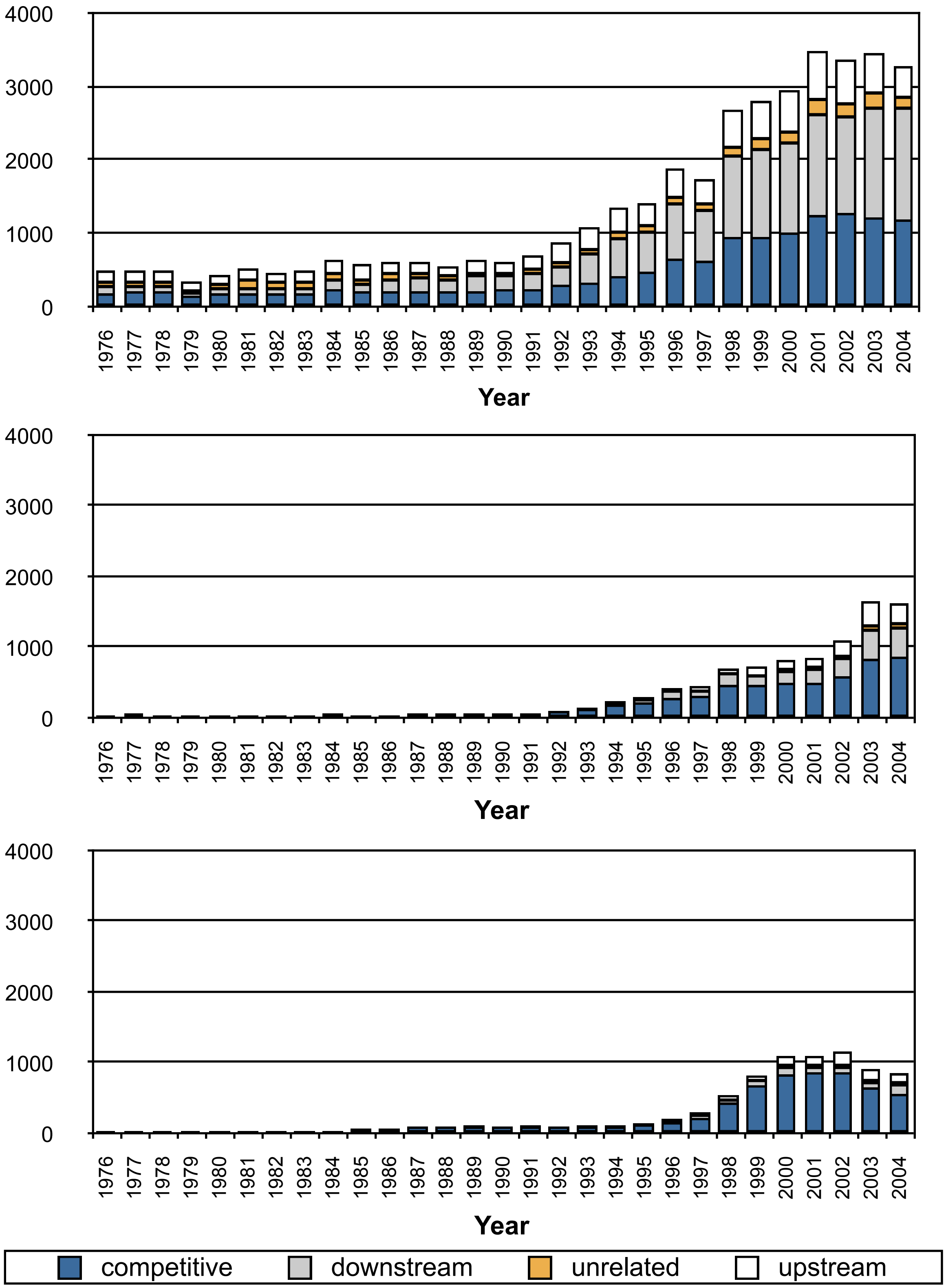

Figure 5: Intel Patents (top) and AMD Patents (Bottom) as a Fraction of IBM Patents

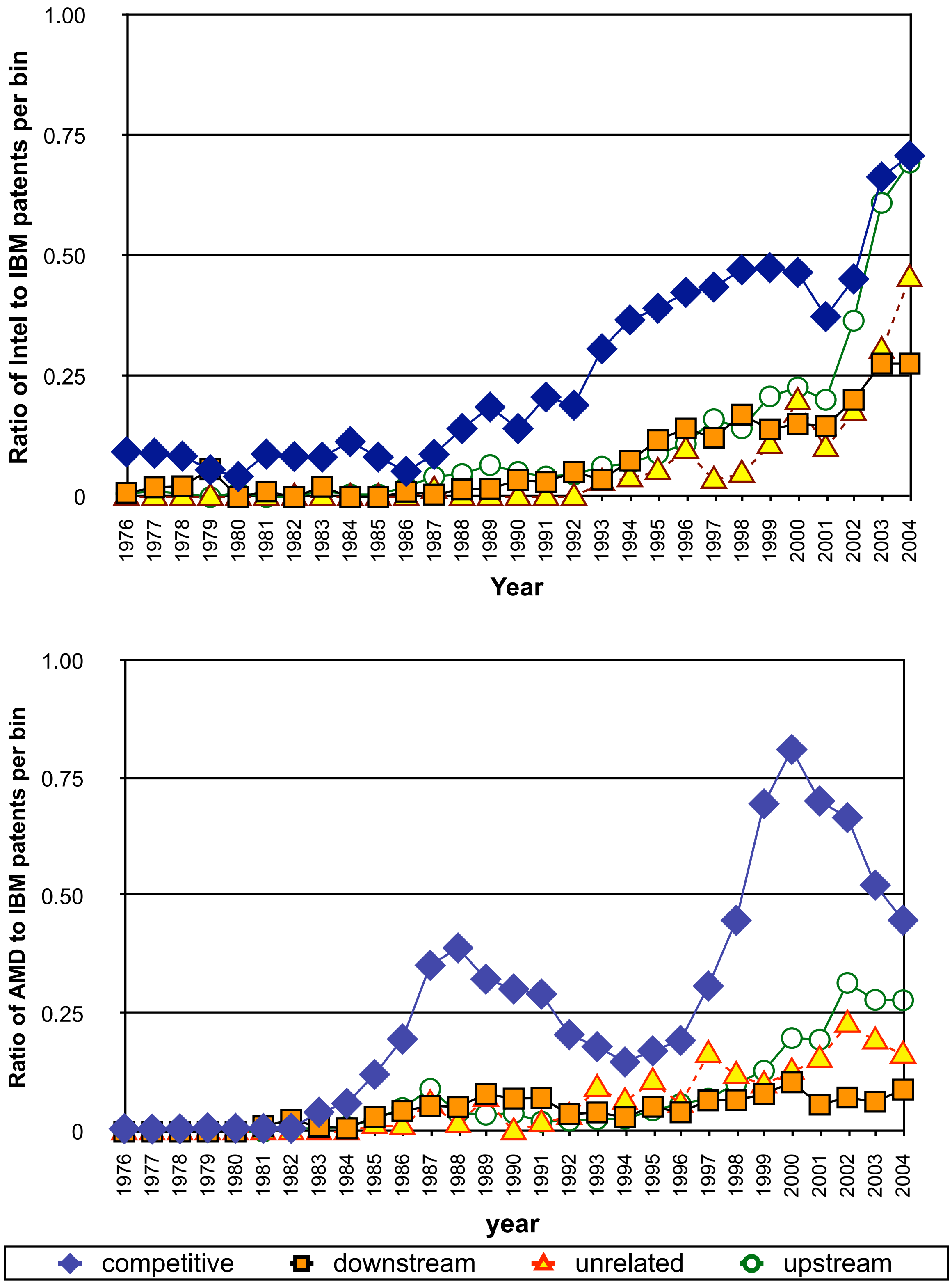

Figure 6: Cross-citation Index: IBM (Top), Intel (Middle) and AMD (Bottom)