(Re-)Integration Dynamics of the PC Platform

by

Chin-Ann Ong

Master of Engineering in Electrical and Electronic Engineering
Imperial College of Science, Technology and Medicine (1997)

Submitted to the Sloan School of Management in partial fulfillment
of the requirements for the degree of

Master of Science in the Management of Technology
at the
Massachusetts Institute of Technology

June 2004

© 2004 Chin-Ann Ong. All rights reserved.

The author hereby grants to MIT permission to reproduce and to distribute
publicly paper and electronic copies of this thesis document in whole or in part.

Signature of Author: ____________________________

Chin-Ann Ong
Sloan School of Management
May 7, 2004

Certified by: ______________________________________

Henry Birdseye Weil
Senior Lecturer, Sloan School of Management
Thesis Advisor

Accepted by: ____________________________

David Weber
Director, Management of Technology Program
(Re-)Integration Dynamics of the PC Platform

by
Chin-Ann Ong

Submitted to the Sloan School of Management on May 7, 2004
in partial fulfillment of the requirements for the degree of
Master of Science in the Management of Technology.

Abstract

Since the 1990's, the PC has come under increasing integration pressure. Many electronic components which had previously existed as separate standalone components have been integrated onto the PC mainboard. Examples include the disk-drive, video, sound and network controllers. Some of these had in fact been de-integrated from the mainboard in the 1980's during the burgeoning years of the PC boom (when the capabilities of on-board electronics could not keep pace with the performance demands) before being re-integrated.

Technological and market forces drive this integration trend. These forces are the result of the complex interaction between technological advances, industry competitors (old and new), suppliers, customers, complementors and potential substitutes for the PC. The forces are often inter-dependent and the dynamic system set up by a combination of all these forces produces the integration paths of the aforementioned components.

Besides integration trends, the future evolution of the PC is another area of great interest. In particular, the roles played by architectural innovation and digital convergence are significant in determining the future utility of the PC, in terms of both its reach (extent of peripheral device coverage) and range (extent of application). The potential of the PC is currently held in check by the limitations of its existing architecture and the confines of the traditional industry boundaries. The removal of both barriers will perhaps lead to a shift of paradigm to that of a virtual PC, which is dynamically constructed (by the intelligent network computer) from shared resources found on the network. This scenario will usher in an era of universal computing - access to information and processing power anytime, anywhere and through any device - which represent today's concept of computing utopia.

Thesis Supervisor: Henry Birdseye Weil
Senior Lecturer, Sloan School of Management
Contents

1. Introduction ............................................................................................................................................. 8
   Motivation.................................................................................................................................................. 9
   Structure of thesis ................................................................................................................................... 9

2. Survey of relevant research and background knowledge ................................................................. 11
   The Double-Helix – framework for analyzing de-integration and re-integration ...................... 11
   Strategic Inflection Points and “10x” change ...................................................................................... 15
   Abernathy-Utterback model of technological innovation ................................................................. 18
   Christensen model - Attack-from-below and Northeast Migration ....................................................... 26
   Henderson-Clark model – defining innovation ..................................................................................... 29
   Competing in an age of modularity ......................................................................................................... 31
   Nested hierarchies and value frameworks ............................................................................................ 33
   Platform leadership ................................................................................................................................. 36
   Digital Convergence ............................................................................................................................... 38

3. (Re-)Integration dynamics .................................................................................................................... 42
   Scope of study ......................................................................................................................................... 42
   Utterback and Christensen analyses of the graphics/video subsystem ................................................. 42
      Evolution of the graphics/video subsystem ........................................................................................ 42
      Emergence of dominant design ........................................................................................................... 44
      Attack from below by integrated video controllers ............................................................................ 47
   Market analysis using the 6-forces framework .................................................................................... 53
      Competitors and Complementors ....................................................................................................... 54
      Customers ................................................................................................................................................ 57
      Substitutes ............................................................................................................................................. 61
      Suppliers ................................................................................................................................................ 64
      New Entrants ......................................................................................................................................... 66
   Model of re-integration dynamics .......................................................................................................... 67

4. More case studies – sound and communication subsystems ............................................................... 70
   Scope of study ......................................................................................................................................... 70
   Communication subsystem - the POTS modem .................................................................................... 70
      History and background ....................................................................................................................... 70
      Analysis of integration path ................................................................................................................. 72
   Audio subsystem – the soundcard ........................................................................................................... 74
      History and background ....................................................................................................................... 74
      Analysis of integration path ................................................................................................................. 76
   Communication subsystem – network controller ............................................................................... 77
      History and background ....................................................................................................................... 77

p. 3 of 112
5. Future of PC platform ......................................................... 86
  Scope of study ........................................................................ 86
  Constructing the scenario space ............................................. 86
  Determinant 1: Prospect of architectural innovation .............. 87
  Determinant 2: Extent of digital convergence ......................... 89
  Partitioning the scenario space ............................................. 90
  Scenario 1: Plodding forward .............................................. 92
  Scenario 2: Unrealized dream .............................................. 93
  Scenario 3: Giant Leap ....................................................... 94
  Scenario 4: Computing utopia ............................................. 95
  Looking into the crystal ball ................................................ 96

6. Conclusion ........................................................................... 99
  Further research topics ........................................................... 99

7. Appendices .............................................................................. 101
  Appendix A – Constructing the performance charts of video controllers ............................................. 101
    Measuring performance of video controllers ......................... 101
    Selecting time frame and representative video controllers .......... 102
    Normalizing performance numbers ....................................... 103
    Determining the market needs ............................................. 106
  Appendix B – Other performance charts of video controllers ......................................................... 108
  Appendix C – Intel’s financial data ........................................ 109

8. Bibliography ............................................................................ 110
Diagrams

Figure 1. The Double Helix ................................................................. 11
Figure 2. Transformation of computer industry from a vertical industry structure and integral product architecture to a horizontal industry structure and modular product architecture .................................................. 14
Figure 3. 6-forces diagram ................................................................. 16
Figure 4. Utterback’s technology/product/service/industry life cycle ........... 21
Figure 5. Dynamics of Utterback model (relating to rates of product and process innovations, and number of firms in the industry) ...................... 22
Figure 6. Performance of an established and invading product, with (a) no response from the established players, and (b) a burst of improvement in the established technology in response to the invasion ......................... 23
Figure 7. The “attack-from-below” phenomenon .................................... 27
Figure 8. A framework for defining innovation .................................... 30
Figure 9. A nested hierarchy of product architectures involving the PC ....... 34
Figure 10. Coming together of industries due to digital convergence .......... 39
Figure 11. Graphical plot of the data in Table 1 .................................... 46
Figure 12. Total graphics market share (in terms of overall unit shipments) in third quarter of 2002. (Source: Jon Peddie Research news release) .................. 46
Figure 13. Performance evolution of discrete top-end video controllers and integrated graphics chipsets ............................................... 48
Figure 14. Shipment of video/graphics chips worldwide per year. (Source: Jon Peddie Research) .............................................................. 50
Figure 15. Q3 2003 market share (in terms of overall unit shipments) of integrated graphics chipsets (IGCs). (Source: Mercury Research news release) .............................................................. 51
Figure 16. 6-forces analysis of the PC business .................................... 53
Figure 17. System dynamics model (causal loop diagram) of factors impacting (re-)integration trends in the PC industry ................................................. 67
Figure 18. Dynamics which correspond to the 6-forces analysis on Complementors/Competitors and Suppliers ............................................. 68
Figure 19. Dynamics which correspond to the 6-forces analysis on Customers and Substitutes ............................................................. 69
Figure 20. Bus network topology .......................................................... 77
Figure 21. Wireless LAN access via 802.11 .......................................... 79

p. 5 of 112
Figure 22: Four general scenarios based on two main determinants... 90
Figure 23: Range and reach of the PC in the four scenarios... 91
Figure B.1: Transistor count, pixel fill-rate and video memory bandwidth of top-end video controllers from ATI and Nvidia... 108
Tables

Table 1: Chip-making firms in the PC video controller industry. ...................... 45
Table 2: Growth rate of consumer and commercial PC shipments in the US, 2001-2004. ........................................................................................................... 50
Table 3: 2003 Financial data of Intel and companies in adjacent or overlapping parts of the PC or Home Network value chains......................................................... 65
Table 4: Summary of V.xx modem standards. ....................................................... 71
Table 5: Comparison of integrated audio solution with the Creative Soundblaster Audigy2 soundcard .......................................................... 75
Table 6: Dell’s desktop PC offerings (March 2004). .......................................... 75
Table 7: Shipments of WLAN adaptors with PCs. ............................................. 79
Table 8: Forecast percent of portable PCs which will ship with WIFI controllers. 80
Table 9: Data speeds supported by the 802.xx standards and broadband modems ................................................................................................................. 81
Table 10: Data rates of some PC communication standards. ............................. 88
Table A.1: Top-end discrete video controllers and integrated graphics chipsets from 1996 to 2003 ......................................................................................... 103
Table A.2: Benchmarks of the selected video controllers. ............................... 105
Table A.3: Current performance needs of the video controller market .......... 106
1. Introduction

IBM created the personal computer (PC) architecture in 1981, only to lose control of the nascent PC industry in 1983 with the appearance of the first Compaq clone. Intel and Microsoft have since famously run away with the crucial microprocessor and operating system segments respectively. In the process, they have assumed leadership of the PC platform through careful cultivation of the dominant Win-tel combination\textsuperscript{1}.

The modular design of the PC architecture also meant that peripherals could be plugged into the PC mainboard, and the peripherals each spawned an industry in the ensuing PC boom. The last two decades have seen the creation and maturation of a wide variety of peripherals – indeed, some of the peripherals have been re-integrated onto the PC mainboard and ceased to be a separate component.

The last few years have seen the coming-of-age of mass-market digital entertainment technologies – a seemingly inevitable fact which was heralded by Microsoft, among others, as early as the mid 1990’s\textsuperscript{2}. Indeed, with the release of the Windows XP Media Center Edition (which has enhanced digital media capabilities) in 2002\textsuperscript{3}, the PC platform seems poised on the verge of a monumental change – there will be an increase in scope of electronic devices which will become peripherals of the PC platform, and it will be exciting to see how the industry develops.


\textsuperscript{3} Miller, Michael J, “Much Ado About Windows ; Windows XP Media Center Edition lets you watch TV on your PC and turns your PC into a personal video recorder”, \textit{PC Magazine}, vol. 21, issue 19, 5 Nov 2002, p. 7-8.
It is therefore an opportune time to review the (re-)integration dynamics of the PC platform as they have unfolded, as well as deduce what the future holds for the PC platform.

**Motivation**

The main motivation for this thesis is to look for plausible answers to two questions which have been intriguing me for some time and are of particular importance to competitors in the PC arena. These questions are:

- What are the forces affecting integration (or substitution) of PC peripherals\(^4\)? In other words, what determined the integration paths of the stand-alone peripherals?
- How will the PC platform evolve in the future?

**Structure of thesis**

Chapter 2 contains a survey of ideas and findings from existing literature which have a bearing on this thesis. In particular, the survey introduces frameworks and models which will be applied and used for analysis in later chapters.

Chapter 3 analyzes industry data (of the video subsystem) based on the frameworks introduced in Chapter 2, so as to gain an understanding of the (re-)integration dynamics that are acting on the PC platform from an innovation and market perspective. From the analysis, a model of the integration dynamics will be proposed.

The dynamic model will be used to analyze the integration path of 2 other subsystems – the sound and communication subsystems – in Chapter 4.

---

\(^4\) For this question, I am referring to those peripherals which comprise solely of electronic circuitry which can be shifted from some stand-alone daughter board to the PC mainboard (eg. video, sound and network controllers). I will also be making a short comment on electromechanical peripherals in a later chapter.
Chapter 5 presents a scenario analysis which hypothesizes on the possible future evolution of the PC platform.

Chapter 6 then concludes by summarizing the findings and identifying areas for possible follow-on research.
2. Survey of relevant research and background knowledge

This thesis draws its inspiration from a wide body of existing research and literature. The pertinent ideas and findings from these works, as well as necessary background knowledge, are presented in this chapter.

The Double-Helix – framework for analyzing de-integration and re-integration

In his book Clockspeed⁵, Charlie Fine used the PC industry as a “fruit-fly” for study, and in the process provided some valuable insights into the industry’s trends from the perspective of market forces of integration and de-integration. The framework which Fine proposed for analyzing these trends is the Double-Helix (see Figure 1).

![Double-Helix Diagram]

**Figure 1. The Double Helix⁶.**

The Double Helix suggests that there is a constant evolution from a vertical industry structure with integral product architecture to a horizontal industry structure with modular product architecture. The process is driven by market forces, including high-dimensional complexity, organizational rigidities, technical advances, supplier market power, and proprietary system profitability. The cycle is driven by pressure to de-integrate and pressure to integrate.

---

⁶ Ibid, p. 49.
structure with modular product architecture, and back again. This evolution is caused by two distinct sets of forces, each acting when the industry/product is in a particular configuration. The combination of niche competitors, the strain of maintaining technological parity across many products (or subsystems) and the organizational rigidity inherent in big market leaders drives vertically-integrated companies toward de-integration and a horizontal industry structure (often with a modular product architecture that allows competition along each "row" of the horizontally-structured industry).

When the industry has a horizontal structure, some subsystem player(s) will inevitably end up with market power (due to control over a scarce commodity in the chain). The power will induce incentives to increase control through bundling with other subsystems and the development of proprietary integral solutions, thereby pushing the industry towards another epoch of vertical integration and integral product architecture.

And such is the case with the PC industry. In his book *Only The Paranoid Survive*\(^7\), ex-Intel CEO Andrew Grove described the computer industry in the 1970's as being dominated by vertically-aligned behemoths like IBM, DEC and HP. Each had products with integral (and proprietary) architectures and there was little or no interchangeability across different companies' products. Each company maintained broad technological, production, sales and distribution competencies across many (if not all) key elements of their own computer systems.

The trigger for change came in the form of a small upstart company called Apple, who launched the first PC in the late 1970's\(^8\). The growing PC market prompted IBM to create a PC division, which eschewed vertical integration and integral product architecture.

---

\(^7\) Grove, Andrew S, *Only the paranoid survive: how to exploit the crisis points that challenge every company*, New York: Currency Doubleday, 1996.

product architectures, and decided on a modular PC architecture instead. Furthermore, in a move which set the stage for a momentous turn of the Double Helix (or in Grove’s terminology – a Strategic Inflection Point⁹), the division made a supply chain decision to outsource the microprocessor to Intel and the operating system to Microsoft. The modular architecture encouraged many companies to enter the industry and supply subsystems: semiconductors, circuit boards, application software, peripherals, network services, and (perhaps most damaging to IBM) PC design and assembly.

Suddenly, the dominant product was no longer the IBM computer, but the IBM-compatible computer. Encouraged by the universal availability of the Win-tel subsystems, PC clone-makers led the way in modularizing the industry. 1985 marked the final turn of the Double Helix into the horizontal industry/modular product mode when Compaq beat IBM to the market with the first 80386-based PC. In the presence of many niche competitors in the various horizontal layers, high complexity of maintaining control and competencies across all the layers, and inability of the relatively rigid behemoths of yesteryears to change fast enough, the vertical industry structure de-integrated. This change in industry structure is graphically represented in Figure 2.

Fine also argues that the horizontal/modular structure is unstable and short-lived. A horizontal industry structure creates intense competition within each layer and over time, weaker players will be driven out. Once a survivor becomes large enough to exert market forces along its row, it sees the opportunity to expand vertically as well. We can already see signs of this happening in the PC industry - re-integration forces have arguably become stronger in the peripherals layer of

---

⁹ It might be interesting for the reader to note that turns of the Double Helix can be said to be one of the Strategic Inflection Points which Andrew Grove warned executives to be wary about (in his book Only the Paranoid Survive). Both Grove and Fine acknowledged that competitive advantages in the fast-paced computer industry are temporary, and companies must always keep an eye on future sources of advantages. Strategic inflection points can also be caused by technological innovations - the so-called "disruptive technologies" whose dynamics are described later in this thesis.
the industry with the maturation of the early generations of peripherals. There are increasing signs that Intel and Microsoft are encroaching into the PC peripheral space. Microsoft has expanded into the applications software, network services and assembled hardware layers as well. According to Fine, these vertical incursions by dominant row players with market power creates re-integration forces which eventually swings the industry back to a vertical industry/integral product mode.

![Vertical industry structure](image)

**Figure 2. Transformation of computer industry from a vertical industry structure and integral product architecture to a horizontal industry structure and modular product architecture**

The final point in relation to the Double Helix concept is that the rate at which the industry structure swings between the two modes depends on the clockspeed of the industry. The two main drivers of clockspeed are competition and technological innovation - an increase in either or both factors will generally generate an uptick in the clockspeed. When there is a drastic advance in technology or change in the basis of competition, then the clockspeed will increase significantly. No where is this more true than the computer industry - the

---

10 Adapted from the book *Clockspeed*, slightly updated to reflect current industry landscape (eg. take-over of DEC by Compaq, and the subsequent merger of Compaq with HP).
on-going convergence of the computer, entertainment, consumer electronics and telecommunication industries\textsuperscript{11} (all with fast clock speeds) will generate frontier spaces in which the pace of innovation and intensity of competition will be high.

**Strategic Inflection Points and “10x” change**

There was an earlier mention that Intel’s and Microsoft’s rise to power (and IBM’s corresponding lost of control) was precipitated by a “strategic inflection point” in the industry. This term was coined by Andrew Grove, and we now turn to his ideas in order to gain a separate but complementary view of the forces affecting integration/de-integration in the computer industry\textsuperscript{12}.

The basis for Grove’s ideas is the 6-Forces analysis of a company’s competitiveness (see Figure 3 for a graphical representation). This model was adapted from Michael Porter’s 5-forces framework for competitive strategy analysis\textsuperscript{13} and included the influence of complementors\textsuperscript{14}. This model can be used to analyze the competitiveness of a company, as well as the structure of an industry.

Grove described the 6 forces which affect the competitive well-being of a business as the intensity of rivalry in the industry, bargaining power of suppliers and customers, threats of substitutes and new entrants, and alignment with complementors. When a change in one of these forces is an order of magnitude larger than what the business is normally accustomed to, there will be a major industry shake-up and the business can lose control of its destiny. Grove called this sort of change a “10X” change.

\textsuperscript{12} Grove, *Only the Paranoid Survive*: Chapter 2.
\textsuperscript{14} Complementors are companies which provide complementary products. See Hax, A.C. and D.L.Wilde II, *The Delta Project: Discovering new sources of profitability in a networked economy*, Palgrave, 2001: Chapter 5 System Lockin – Winning through complementors.
After a “10X” change occurs, the industry will eventually reach a new equilibrium in which some businesses are stronger and some businesses are weaker. Whether a business becomes stronger or weaker depends on the skill with which managers navigate through the “strategic inflection point”. An inflection point occurs where “the old strategic picture dissolves and gives way to the new”, or in other words, “when the balance of forces shifts from the old structure, from the old ways of doing business and the old ways of competing, to the new”.

In the computer industry, the “10X” change in the early 1980’s was the rising power of Intel and Microsoft as suppliers to IBM, which eventually led to the transition of industry structure from one which was vertically-aligned to one which was (and still is) horizontally-aligned. The period of transition represented a “strategic inflection point” (corresponding to a turn of the Fine’s Double-Helix).

---

15 Grove, Only the Paranoid Survive: p. 29.
Since this major inflection point, the PC industry has seen a number of minor inflection points – not quite a “10X” change, but sufficiently significant to result in some permanent change in the industry structure. Of most interest to this thesis are those inflection points which involved the shifting of the basis of competition for particular PC peripherals or the introduction of new categories of peripherals. These include:

- **A change in the customer’s basis of choice due to the coming-of-age of an erstwhile lower-performing (and unacceptable) substitute.** The substitute has finally reached an acceptable level of performance based on the old set of product attributes used for comparison, so the customer’s focus shifts to other attributes. A recent example of this phenomenon is the wild success of the Centrino processor from Intel, which was launched in mid-2003. Intel deemed correctly that the processing power of mobile processors (e.g. the Pentium4 mobile processor) was more than sufficient to meet the needs of most laptop users, and customers’ focus has shifted to other attributes like battery life and ease of connectivity. Hence the Centrino - a processor running at a slower clock-speed but consuming much less power\(^{16}\). It will be interesting to investigate the stand-alone PC peripherals which were overtaken, or are in danger of being overtaken, by on-board chipsets based on this phenomenon\(^{17}\).

- **The appearance of enabling PC applications.** The set of devices which can be classified as PC peripherals is not static but constantly changing (mostly increasing in scope) in response to the range of applications possible with the PC. Since the advent of the PC, there have

---

\(^{16}\) Ease of connectivity in a Centrino laptop is provided by a separate wireless networking chip on the laptop mainboard.

\(^{17}\) This phenomenon is also called the “attack-from-below” by Clayton Christensen and will be discussed later in this thesis. An on-board chipset refers to a circuitry which is integrated onto the PC mainboard and performs a particular functionality.
been a few waves of enabling applications, and each successive wave introduced a new generation of peripherals. These waves of enabling applications are arguably (in chronological order) spreadsheet, word processing, desktop publishing, email, internet browsing and online information searching\(^{18}\). It will be worthwhile to examine the impact of these successive waves of enabling applications, since each wave might be a catalyst for further de-integration and product innovation\(^{19}\).

Last but not least, the 6-forces framework can be used to analyze the rise and ebb of the 6 forces to determine industry-structural conditions which are favorable for de-integration or re-integration.

**Abernathy-Utterback model of technological innovation**

The PC industry is heavily dependent on technology, and it should be obvious from the preceding discussion that technological innovation plays an important role in the industry dynamics. Indeed, it has been mentioned earlier that technological innovation is a main driver of an industry’s clockspeed. There are various frameworks which can be used to analyze the dynamics of technological innovation.

The Abernathy-Utterback model (henceforth referred to as the Utterback model) first appeared in writing in the June/July 1978 edition of Technology Review\(^{20}\),

---

\(^{18}\) This list was suggested in Levy, Steven, “Twilight of the PC Era?”, Newsweek, 24 Nov 03, vol. 142, issue 21: p. 54. I would add GUI, gaming and digital multimedia to the list. Furthermore, in this age of digital convergence, we need to also consider the applications involved in the current digital revolution – home entertainment/networking and ubiquitous computing.

\(^{19}\) For example, the double helix would suggest that a new enabling application provides impetus for a de-integrated and horizontally-aligned industry, since the new application introduces new niche competitors and increases the dimensional complexity. Would the waves of enabling applications be a primary reason why the PC industry has remained stubbornly horizontally-aligned for close to two decades now?

and later expounded on in the book *Mastering the Dynamics of Innovation*\(^{21}\). There are two powerful concepts in the Utterback model which are of particular relevance to the topic at hand – (1) the relationship between rates of innovation, the marketplace and the participating firms, and (2) the invasion of an established business by a radical innovation.

The Utterback model is a dynamic model which suggests inter-dependent rates of product and process innovation over time, which in turn influence the underlying dimensions of product, process, organization, market and competition. Utterback posited that when a radical new technology is introduced to the market, there is an initial explosion of product innovation (and hence product variety) and a rapid entry of new firms. Since there are many small firms with unique products, the market is fragmented and unstable with diverse products. The firms are usually entrepreneurial and organic in form to deal with rapid market feedback (on the success or failure of products).

Once a dominant design\(^{22}\) emerges out of all the technological and market experimentation, the competitive emphasis then shifts from product innovation to process innovation. This shift marks the beginning of a period of shakeup in the industry and the number of competing firms gradually falls. Utterback and Suarez\(^{23}\) suggested that

> A dominant design has the effect of enforcing standardization so that production economies can be sought. Effective competition can then take place on the basis of cost as well as product performance ....... Firms that are not able to make the transition toward greater product standardization and process innovation will be


\(^{22}\) The issue of Dominant Designs (eg. definition, emergence) is a research area in and of itself. For this thesis, Utterback’s definition (from *Mastering the Dynamics of Innovation*) should suffice – “a dominant design embodies the requirements of many classes of users of a particular product, even though it may not meet the needs of a particular class to quite the same extent as would a customized design”, and “a dominant design drastically reduces the number of performance requirements to be met by a product by making many of those requirements implicit in the design itself”.

unable to compete effectively and will eventually fail. Others may possess special resources and thus successfully merge with the ultimately dominant firms. Some weaker firms may merge and still fail. Overall, a firm's inability to change its organization structure and practices along with the evolution of technology in the industry will be a major source of failure.

A further refinement to the Utterback model was made by Christensen, Suarez and Utterback\(^{24}\) when they related the likelihood of a firm's survival (especially that of a new entrant) with its technological and market strategies. An analysis of data from the rigid disk drive industry led them to summarize that:

.... (a) firms that adopt the dominant design features will be less likely to exit from the industry; (b) firms that enter the industry during the “window of learning” just prior to the emergence of the dominant design will be less likely to exit; and (c) firms that introduce architectural innovations into new markets will be less likely to exit.

Surviving firms become increasingly mechanistic (reflecting the emphasis on production economy) and there is usually a concerted drive towards control over the value chain (vertical integration is one possibility of achieving such a control\(^{25}\)). The market becomes commodity-like with largely un-differentiated products. Eventually, only a few relatively large firms with consistent sales and market share remain, and the market stabilizes. The industry then awaits the next major technological discontinuity to kick-start the cycle again. This cycle is graphically shown in Figure 4.

Figure 5 shows the dynamics (relating to rates of product and process innovation, and number of firms in the industry). Utterback partitioned the dynamics into 3 phases – fluid, transitional and specific. Each phase exhibits different characteristics along the dimensions of Innovation, Sources of Innovation,


\(^{25}\) Utterback and Suarez (1993) suggested that only when relationships with suppliers are not enough will there be a drive among producing firms toward vertical integration, to capture those elements of supply which pose the greatest uncertainties for them. An example of a cooperative relationship is the Japanese Keiretsu model which adopts an extended enterprise view of the firm – see Dyer, Jeffrey H, “How Chrysler Created an American Keiretsu”, Harvard Business Review, Jul-Aug 1996.
Products, Basis of Competition etc. It will be interesting to determine whether data from the PC peripherals industry follow these dynamics and behavior.

Figure 4: Utterback’s technology/product/service/industry life cycle

---

26 A full list of the characteristics is presented in a table format in *Mastering the Dynamics of Innovation*: p. 94-95.
Figure 5. Dynamics of Utterback model (relating to rates of product and process innovations, and number of firms in the industry)\textsuperscript{27}.

The second concept from the Utterback model which can be applied to this research area is the invasion of a stable business by a radical innovation. A radical innovation is one which has the potential to deliver a greatly improved product performance or lower production costs, or both. As such, the appearance of a radical innovation generally creates a period of discontinuity in which major product or process changes occur, new businesses are created, and existing businesses are either transformed or destroyed (ie. a new fluid phase is introduced). Utterback suggested that this is a recurring phenomenon in many

\textsuperscript{27} Utterback, Mastering the Dynamics of Innovation:Chapter 4.
industries, and there is a general pattern to the invasion process. This pattern is graphically illustrated in Figure 6.

![Graph showing performance of established and invading products](image)

**Figure 6.** Performance of an established and invading product, with (a) no response from the established players, and (b) a burst of improvement in the established technology in response to the invasion\(^{28}\).

Figure 6(a) shows that the new technology usually debuts as a product (at time \(t_1\)) with lower performance (and usually cost as well) when compared to the existing product. The performance gap usually prevails for some time, until the new technology enters a period of rapid improvement, typically just as the existing technology experiences a slowdown in improvements. There comes a time when the performance of the invading product catches up with (at time \(t_2\)) and then exceeds that of the established product.

However, established players will usually react to the invading technology:

> Purveyors of established technologies often respond to an invasion of their product market with redoubled creative effort that may lead to substantial product improvement based on the same product architecture\(^{29}\).

\(^{28}\) Ibid: p. 159-160. Note that for cases in which cost is the chief determinant of the outcome, these 2 figures can be inverted to describe declining cost curves for the established and invading products.
Figure 6(b) shows this behavior. Due to the late burst of improvement, the incumbent technology enjoys an extended period of superiority. However, the performance soon peters out again, and the relentless pace of improvement in the new technology allows the invading product to equal (at time $t_3$), and then surpass, the established product.

These two concepts from the Utterback model can be used to study the re-integration of PC peripherals into the PC mainboard\textsuperscript{30}. The first concept says that when the market stabilizes in the specific phase, players with market power (ie. Microsoft and Intel) will attempt to expand vertically in order to exert more control over the value chain and hence provide impetus for re-integration. The decreasing rates of innovation in the specific phase might also be a factor that prompts the platform leaders to start the process of re-integrating the particular peripheral into the mainboard and hence reduce the amount of uncertainty for themselves (since the uncertainty now outweighs the marginal gain to the platform’s attractiveness from any continued incremental innovation). It takes a radical innovation-induced discontinuity to drive the market to another fluid phase and thus provide fuel for de-integration once more.

The video controller segment of the PC Peripherals market seems to demonstrate this behavior. This market segment has arguably seen two radical innovation – the first being the creation of the VGA standard that gave rise to the first generation of video cards\textsuperscript{31} in the late 1980’s/early 1990’s, and the second being

\textsuperscript{29} Ibid, p. 159.

\textsuperscript{30} The microprocessor and the PC mainboard (on which resides the chipset) together form the core products of the PC architecture, since they contain the crucial architectural elements (eg. controllers for the various buses and interfaces).

\textsuperscript{31} VGA stands for Video Graphics Array, and was introduced by IBM in 1987. The first VGA circuitry was found in the IBM PS/2 systems, implemented as a single VLSI chip which was integrated onto the mainboard. IBM also created a VGA video card which can be plugged onto the mainboards of earlier IBM machines via a 8-bit interface slot. The standard VGA could produce up to 256 colors (from a palette of 262,144 colors) at a resolution of 320x400. The later SVGA (Super VGA) standard could support millions of colors at a choice of resolutions. Thanks to the appearance of the Windows operating system with its GUI, SVGA cards were popularly called “Windows Accelerators” or “Graphics Accelerators”.

p. 24 of 112
the introduction of 3D processing capabilities in the mid 1990's. In both cases, there was an initial influx of competing firms, followed by a period of consolidation. Towards the end of the 1990's, Intel made its first vertical foray into the video controller segment by integrating the video controller circuitry into the mainboard itself. This integrated circuitry used a portion of the system's RAM\textsuperscript{32} instead of using dedicated RAM like most video card.

Due to its poor performance, the integrated video controller circuitry is currently found only in low-end systems which require rudimentary video processing capability. The mid- to high-end market tiers are still dominated by video card manufacturers (eg. nVidia and ATI) who refresh their line-ups every 6 months. The obvious question is - will the integrated video controller circuitry ever displace the video card?

The second concept from the Utterback model seems to indicate so. Even though the performance gap is pretty big now, Moore's Law\textsuperscript{33} and the ever-improving semiconductor technology suggest that the computing power of processors and bus speeds will one day be fast enough to increase the power of integrated video controller circuitry (and indeed, any integrated circuitry) dramatically. The integrated video controller circuitry might not overtake the video card for a good many years, but it does not need to - as long as the market demand for performance increases at a slower pace than the performance of integrated video controller circuitry, the integrated circuitry will gradually but surely invade all market tiers from bottom up, and then its lower cost will drive out the video card.

\textsuperscript{32} This architecture is called the Unified Memory Architecture.

\textsuperscript{33} Moore's Law was postulated by Gordon Moore, a co-founder of Intel, in 1965. It basically says that there will be doubling of transistors every couple of years, or to be more exact, that the power and capacity of integrated circuits would double every eighteen months. Remarkably, it has held true for nearly 40 years.
Christensen model - Attack-from-below and Northeast Migration

Clayton Christensen described this “progressive invasion of market tiers from below” phenomenon in his book *The Innovators Dilemma*. He called it the “attack from below”, and his ideas provide an insightful interpretation of Utterback’s performance curves.

The chance for an “attack from below” opens up when there is a performance oversupply in the market. A performance oversupply occurs when “technologists are able to provide rates of performance improvement that have exceeded the rates of performance improvement that the market needs or is able to absorb”. This situation creates an opportunity for a disruptive technology to emerge and subsequently invade established markets from below.

Figure 7 illustrates the “attack from below” phenomenon. The dotted (brown) lines represent the demand in the various market tiers in terms of the product attribute used as the main basis of competition. The solid (blue) lines represent the level of the established and invading technologies. For the purpose of this research, it is reasonable to assume that the rate of technological improvements will always be faster than the growth in demand – Christensen, Johnson and Rigby concluded that:

> The pace of technological progress in almost every industry outstrips the ability of customers in any given tier of the market to make effective use of the improved versions of a product. Technologies that aren’t good enough to address customers’ needs at one point typically improve to provide more than enough performance for those same customers at a later point.

---


35 For example, the main basis of competition for video controllers today is the product performance (i.e. processing speed), measured in terms of MIPS (millions of instructions per second).

Figure 7 shows a scenario in which improvements in the established technology has carried it past the demand of the mid-tier market segment. There is thus performance oversupply from the viewpoint of the lower-tier market segment, and an attacker has exploited this opportunity to introduce an invading technology with lower performance, which nevertheless is able to satisfy the lower-tier demand at time $t_1$. When this happens, customers in the lower-tier indicate their satiation by shifting the basis of competition to another attribute.

In PC video controller market, the video card (established technology) and integrated video controller circuitry (invading technology) have shown similar trajectories to the above example. The main basis of competition is processing power, and the video card makers have upped the ante regularly in order to keep up with the demands of sophisticated 3-D processing engines in modern computer games and rendering software. In other words, the companies have set their sights firmly on the top tier of the market. This has left a performance oversupply situation which has been exploited by the purveyors of integrated
circuitry. Although its performance is modest, the integrated circuitry has sufficient performance to satisfy the users of the low-end machines. As such, these users have shifted their basis of choice from performance to price. Since the integrated circuitry costs less than a separate video card, it is only logical that these users choose the integrated circuitry. In fact, all of Dell’s sub-$1000 home-use PCs today (ie. the Dell Dimension 4600C, 4600 and 2400) ship with the Integrated Intel Extreme 3D Graphics circuitry.

Christensen also described another phenomenon – the “northeast migration”. Christensen observed that leading (established) companies migrate readily towards high-end markets, but find it difficult to move downmarket, because “in good companies, resources and energy coalesce most readily behind proposals to attack upmarket into higher-performance products that can earn higher margins”. Therefore, when faced with intense competition from the invading technology and rapidly-declining margins in the invaded lower market tiers, established players naturally seek the solace of higher tiers which are as-yet not invaded and margins are still attractive. The players either abandon the lower-tiers totally or offer token competition with cheaply-priced products. In the example shown in Figure 7, the established technology is heading for the highest market tier while the invading technology takes over the lowest tier. Note that if the rates of increase in technologies and market demand remain constant, then the invading technology will eventually penetrate the highest tier and sound the death-knell for the established technology. When viewed in the context of competition between the established and invading technology, the “northeast migration” can be interpreted as a retreat upmarket.

The PC video controller market also demonstrates “northeast migration”. As mentioned earlier, leading video card companies benchmark their technology against the needs of the highest market tier, and release increasingly powerful cards every 6 months. When confronted by the integrated circuitry in the lowest market tier, the companies more or less abandoned the tier, and concentrate their efforts in the middle and high-end tiers.
Therefore, Christensen's model should provide a suitable framework for an in-depth analysis of the dynamics in the video controller segment of the PC Peripherals industry. It will be interesting to determine if other peripherals lend themselves to this framework of study.

**Henderson-Clark model – defining innovation**

The Utterback and Christensen models are highly useful frameworks for investigating past dynamics. The third and final set of innovation dynamics covered here will give a more forward-looking perspective and help to shed some light on the future direction of PC peripherals, by looking at possible factors that shape the strategies of platform leaders.

The ideas of Henderson and Clark\(^{37}\) provide a good starting point. They argued that the classification of innovation as either incremental or radical is misleading; instead, one should focus more on the distinction between the product components and architecture. This argument stems from the fact that successful product development requires two types of knowledge – (1) component knowledge, ie. knowledge of each of the core design concepts and how these are implemented in each of the components, and (2) architectural knowledge, ie. knowledge about how the individual components are integrated/linked to become a coherent system. When viewed along these two dimensions, innovation can be categorized into four forms, as shown in Figure 8.

The horizontal dimension in Figure 8 captures an innovation's impact on components, while the vertical one captures its impact on the system architecture. The four types of innovation can be defined as follows:

- **Radical innovation** establishes a new dominant design and, hence, a new set of core design concepts embodied in components that are linked together in a new architecture. **Incremental innovation** refines and extends an established design. Improvement occurs in individual components, but the underlying core design

---

concepts, and the links between them, remain the same. Modular innovation changes a core design concept without changing the product's architecture. The essence of an architectural innovation is the reconfiguration of an established system to link together existing components in a new way.\(^{38}\)

![Core Concepts Table]

Figure 8. A framework for defining innovation\(^{39}\).

These ideas suggest that from the viewpoint of a platform leader (ie. an entity which holds significant control over a platform's architecture, eg. Intel and Microsoft in the PC platform), incremental and modular innovations pose little threat – indeed, these innovations usually extend the attractiveness of the platform. On the other hand, radical and architectural innovations destroy the value of the leaders' architectural knowledge (and control) and pose serious threats. Henderson and Clark argued that an architectural innovation is perhaps a more insidious threat to the platform leader, since

\[\ldots\text{radical innovation creates unmistakable challenges for established firms, since (\ldots) it destroys the usefulness of both architectural and component knowledge. Architectural innovation presents (\ldots) a more subtle challenge. Much of what the firm knows is useful and needs to be applied in the new product, but some of what it knows is not only not useful but may actually handicap the firm. Recognizing what is useful and what is not (\ldots) may be quite difficult for an established firm because of}\]


\(^{39}\) Ibid, p. 12.
the way knowledge – particularly architectural knowledge – is organized and managed.

**Competing in an age of modularity**

The PC has a modular architecture. The ideas of Henderson and Clark suggest that a platform leader in the PC industry should adopt a strategy that (1) maintains the leadership through intelligent management of incremental and modular innovations in the components, and (2) monitors the industry for possible architectural or radical innovation (so that the firm can get involved early).

Regarding the first part of the strategy, Baldwin and Clark suggested some guidelines for maintaining leadership in an age of modularity. They claimed that modularity is responsible for the rapid pace of change and innovation in the computer industry, and therefore strategies based on modularity are the best way to deal with the fast clockspeed.

Modularity in design is achieved when designers partition information into visible design rules and hidden design parameters. Visible design rules refer to the architectural decisions, including the interfaces between the components and standards. Hidden design parameters are decisions that determine the implementation of a particular component and do not affect the overall design. Baldwin and Clark suggested that the strategies for competing in a modular marketplace are: (1) as an architect that creates (and controls) the visible design

---

42 According to Baldwin and Clark, "for an industry like computers, in which technological uncertainty is high and the best way to proceed is often unknown, the more experiments and the more flexibility each designer has to develop and test the experimental modules, the faster the industry is able to arrive at improved versions". This is perhaps another reason for the fast clockspeed in the PC industry.
43 It seems plausible to make the following connection between the ideas of Henderson & Clark (1990) and Baldwin & Clark (1997) - incremental and modular innovations are constrained to individual components and therefore affect only hidden design parameters; however, radical and architectural innovations overturns the product architecture and therefore affect the visible design rules.
rules, or (2) as a designer of components that conform to the visible design rules. A company can derive advantage from either role as follows:

For an architect, advantage comes from attracting module designers to its design rules by convincing them that this architecture will prevail in the marketplace. For the module maker, advantage comes from mastering the hidden information of the design and from superior execution in bringing its module to market. As opportunities emerge, the module maker must move quickly to fill a need and then move elsewhere or reach new levels of performance as the market becomes crowded. The architect is in a position of power. Intel has reached the position as the architect/leader of the PC platform by developing a proprietary architecture and leaving the mundane details of hidden modules to others. However, the architect has to keep an eye out for a challenger who “can rely on modularity to mix and match its capabilities with those of others and do an end-run around an architect”. For example in the PC industry, AMD has risen to pose a credible challenge to Intel by rolling out its own microprocessor and mainboard architecture that works with existing PC components.

The second part of the strategy calls for the monitoring and detection of radical and architectural innovations. How can this be done? Baldwin and Clark suggested that a company not only has to monitor its direct competitors, but also need to maintain a vigilant scan on threats and opportunities arising elsewhere. They claim that

Success in the marketplace will depend on mapping a much larger competitive terrain and linking one’s own capabilities and options with those emerging elsewhere, possibly in companies very different from one’s own.

---

Nested hierarchies and value frameworks

Christensen and Rosenbloom\(^{47}\) had the same ideas regarding the monitoring and detection of radical and architectural innovations as Baldwin and Clark, but expressed them to a greater detail in terms of nested hierarchies and value frameworks. The concept behind nested hierarchies is the realization that "products which at one level can be viewed as complex architected systems act as components in systems at a higher level". Therefore, any given system-of-use is made up of a hierarchically nested set of constituent systems and components.

An example involving the PC is shown in Figure 9. The example shows that the video controller has an architecture comprising components like video memory etc., but is itself a component of the PC architecture. The PC itself is a component of the home network architecture. Another level up, the home network can be seen to be a component in the architecture of a ubiquitous computing network.

The value network is the nested commercial system which is inherent in the nested hierarchies, or more specifically:

\[ \ldots \text{ a nested network of producers and markets through which the tradeable architected components at each level are made and sold to integrators at the next higher level in the system}^{48}. \]

In other words, the value network is "the context within which the firm identifies and responds to customers' needs, procures inputs and reacts to competitors".

Now, consider the PC architectural level shown in Figure 9. Looking at the nested hierarchy framework, it seems logical to suggest that the sources for modular and incremental innovation will come from the components at the level of the PC architecture or any of its (lower) nested architectures (eg. the video


\[^{48}\text{Ibid, p. 240.}\]

p. 33 of 112
controller, hard-disk, sound controller), whereas the sources for radical and architectural innovation will come from a higher architectural level or a parallel nested hierarchy (eg. one that nests down from Mobile Appliances rather than Home Network at the highest level). This unique insight points to two obvious forms of radical or architectural innovation which will disrupt the PC – (1) A fellow component of the home network architecture emerges to become a superior substitute, and (2) the Home Network architecture re-aligns itself such that the functionalities of the PC are no longer needed.

![Diagram of Architecture of Ubiquitous Computing Network](image)

**Figure 9. A nested hierarchy of product architectures involving the PC**

---

49 Adapted from the diagram on Christensen and Rosenbloom (1995): p. 238, which showed the nested hierarchies involving the disk drive. Note that the architectures of the home network and ubiquitous computing network are simply my own conjectures, based on information and "vision statements" gleaned from trade publications.

p. 34 of 112
This means that the architect/leader of the PC platform not only has to monitor the PC architecture and those of its components (for direct threats to the leadership position), but also maintain a vigilant scan on higher architectural level(s) or a parallel nested hierarchy. Players in the PC industry have long kept their eyes on the rapid convergence of the computer, telecommunications, consumer electronics, media and publishing, and entertainment industries. This so-called “digital convergence” is arguably the biggest force that is driving change in the nested hierarchies and value networks of all the industries involved, and creating impetus for architectural and/or radical innovations.

In light of this, one can expect a player in the PC industry to extend its reach, control and surveillance by not only integrating vertically within the PC architecture, but also vertically up into a higher architectural layer such that the risks of obsolescence or substitution are reduced. For example, Microsoft has been active in the Home Network and Ubiquitous Computing layers. It released the Xbox in 2002 to compete with other Home Entertainment Center devices. Also, its SmartPhone and Windows Mobile operating systems power mobile appliances.

A movement upwards to a higher hierarchical layer also represents an opportunity – the moving company can increase the functionalities of its architecture such that it creates a radical or architectural innovation to disrupt a fellow component at the higher hierarchical layer. For example, with the release of the Windows XP Media Center Edition, Microsoft expanded the coverage of the Windows OS and made the PC an effective substitute for Home Entertainment Centre devices (eg. stand-alone DVD players, gaming devices). I am most tempted to call this a cumulo-nimbus or mushroom expansion – upwards and then outwards. Note that if a “mushroom expansion” succeeds in encompassing critical components in the

---


p. 35 of 112
higher hierarchical layer, then the expanding company will probably obtain market power and become an architect of that layer over time.

Therefore, the nested hierarchy framework allows us to derive some hints regarding the future of PC peripherals by charting the PC platform leaders' "mushroom expansion" plans. Any device which can be connected to the PC via some means and be recognized by the OS will become a peripheral.

**Platform leadership**

Baldwin and Clark’s notion about maintaining leadership in an age of modularity is but one component of a broader set of concepts relating to platform leadership. Gawer and Cusumano defined the modern high-tech platform as follows:

> ...an evolving system made of interdependent pieces that can each be innovated upon. This definition highlights two fundamental phenomena currently impacting the high-tech world: (1) the increasing interdependency of products and services and (2) the increasing ability to innovate by more actors in the high-tech world.\(^{51}\)

The emphasis is on interdependency and innovation because the essence of platform leadership lies in the recognition that a core product has little value by itself but can be extremely valuable as the center of a network of complements, and innovation by complementors increases the attractiveness of the platform to consumers.

The power of the platform in today’s fast-moving high-tech world was recognized even in the early 1990s. Morris and Ferguson (1993) claimed that

> While any single product is apt to become quickly out-dated, a well-designed and open-ended architecture can evolve along with critical technologies, providing a fixed point of stability for customers and serving as the platform for a radiating and long-lived product family.\(^{52}\)

A platform leader is a firm which typically has market leadership in platform environments and plays a central role in evolving the platform and maintaining the


platform integrity. Examples of platform leaders are Intel (PC hardware platform), Microsoft (PC software platform) and Cisco (internet-based interoperable networking equipment platform). Gawer and Cusumano suggested that platform leadership strategies can be analyzed or defined in terms of the 4-levers framework. The 4 levers are:

- **Lever 1: Scope of the firm.** This lever deals with what the platform leader does inside, and what it encourages complementors to do outside. To a certain degree, this lever reflects what the platform leader deems to be the core product and critical complements of the platform, since these are best done inside. For example, Intel concentrates its business around the microprocessor (core product) and the chipset (key complementary product); Microsoft delivers not only the Windows operating system (core product), but also the Office suite of productivity tools (key complementary product).

- **Lever 2: Product Technology (architecture, interfaces, intellectual property).** This lever deals with decisions regarding the architecture of the core product and the broader platform, in particular the degree of modularity, the degree of openness of the interfaces to the platform, and how much interface information to disclose. Baldwin and Clark's ideas chiefly relate to this lever. Modularity in product design is seen to be a key enabler of a platform strategy, since it allows innovation by complementors to proceed independently of each other and hence lowers the complexity and cost of innovation. In relation to this lever, Gawer and Cusumano also pointed out that "since platforms are made of components that interact following standard interfaces, standard wars are necessarily part of platform strategies."

---

• **Lever 3: Relationships with external complementors.** This lever looks at the relationship between the platform leader and the complementors – whether collaborative or competitive in nature (or both), how consensus is achieved and how conflicts are resolved. For example, Intel places emphasis on trust-building and implemented elaborate programs to work with complementors, helping them to gain industry credibility and raise capital, as well as assisting in technical issues.

• **Lever 4: Internal organization.** This lever looks at how the platform leader organizes its internal structure to manage external and internal conflicts of interest more effectively. For example, Intel maintains a strict separation between groups that have to build consensus with complementors and product groups that compete directly in the complementary space.

Coherence among choices made on these 4 dimensions is of utmost importance - choices made in Levers 2 to 4 have to support the decision of what to do inside and what to leave to complementors (Lever 1).

**Digital Convergence**

The notion of digital convergence has been around for decades, but the hype truly started to take off in the early 1990’s when services such as video-on-demand, interactive television and on-line commerce started to sound quite plausible with the advent of the world-wide web.

From a product viewpoint, Yoffie defined digital convergence as

... the unification of functions – the coming together of previously distinct products that employ digital technologies.... In its simplest form, convergence means the uniting of the functions of the computer, the telephone and the television set\(^{55}\).

Covell has another definition from a technology viewpoint:

---

Digital convergence is the merging of [these] improved computing capabilities, new digital multimedia technologies and content, and new digital communications technologies. This combination of computing power and functionality, digital networked interconnectedness, and multimedia capability enables new forms of human interaction, collaboration, and information sharing\textsuperscript{56}.

The manifestation of these two viewpoints is the current coming-together of the computing, communications, consumer electronics and info-tainment (ie. information and entertainment, which includes media and publishing) industries, the first three being chiefly concerned with the content delivery mechanism and the last with content creation and management. Figure 10 gives a graphical representation of this industry convergence.

![Diagram showing the overlap of computing, communications, consumer electronics, and info-tainment industries]

\textbf{Figure 10.} Coming together of industries due to digital convergence.

The areas of overlap represent convergent spaces where industry boundaries have blurred, and in which there is most innovation and intense competition as companies attempt to achieve dominant market positions and/or come up with the killer application or product. In Utterback's parlance, many products in these overlap areas are still in fluid phase. Since the products and services offered in these areas cuts across multiple industries (in both functionalities and value chain), companies find themselves matched up against competitors from other industries.

\textsuperscript{56} Covell, Andy, Digital Convergence: How the merging of computers, communications, and multimedia is transforming our lives, Aegis Publishing Group, 2000: Chapter 1.
Take for example digital music. Apple (from the Computing industry) launched the iTunes Music Store in April 2003. Apple licenses songs from the record labels in the Info-tainment industry and then stores the digitized songs, using its own proprietary Advanced Audio Coding (AAC) format, on iTunes. A user can download any song for 99 cents and then play the song on his computer or on a portable audio device. iTunes users are currently limited to the iPod portable audio device from Apple, but users of other online music stores like MusicMatch (which uses the Microsoft's WMA encoding format) can select from a wide variety of devices made by companies from both the Consumer Electronics and Computing industries (eg. Philips, Samsung, Panasonic, Sony, Creative, Dell, Gateway). At this moment, song downloads are available only over the internet, but it is plausible that future portable devices can connect to the online music stores directly over wireless networks, a situation which will then involve players from the Communications industry. So, the value chain (from song creation, delivery and finally playing on an audio device) involves players from all the convergent industries.

The iTunes music store is doing very well, with 17 million song downloads in 7 months\textsuperscript{57}. This has been sufficient to tempt other big players into the market. Notable competitors are the MusicMatch (which has partnered Dell), Napster (which was relaunched by the CD-burning software company Roxio) and a number of upcoming stores (eg. Connect by Sony, MyCokeMusic.com by Coca-Cola\textsuperscript{58}). Some of these new online stores will be using their own proprietary encoding format – we will soon see a full-blown standards war as the big guns stake out their share of this burgeoning market. Indeed, a standards war is one of the characteristics of an industry in Utterback’s “fluid phase”.

\textsuperscript{57} Gibson, Owen, “Coke puts fizz into music downloads”, \textit{The Guardian Newspaper}, 8 Dec 03.
\textsuperscript{58} Ibid. MyCokeMusic.com is probably Coca-Cola’s response to the marketing partnership between Pepsi and iTunes which was announced in Oct 03.
The impact of digital convergence on PC peripherals will likely be an increase in scope of functionalities as the boundary of the PC platform expands with the blurring of the industry boundaries – leaders in the Computing industry will be leveraging on the strong PC platform to launch attacks into the convergent spaces. In the recently concluded Consumer Electronics Show (CES) 2004, the CEO of Creative Technology Ltd commented:

"We have won the Best of CES award two years in a row, yet in two entirely different product categories. This shows how Creative is leveraging the power of the PC to become a force to be reckoned with in consumer electronics. It also shows that a cutting edge and innovative product from Creative, a leader in the PC space, can win hearts and minds in the consumer electronics space."

He made the comments in an interview after the Creative Zen Portable Media Center won the "Best of CES" award for the Portable Audio and Video category. The Creative Zen is the first of such devices to be launched, and is based on the Microsoft XP Media Center Edition. It was developed in partnership with Microsoft, and shows that at least some of the PC industry leaders are moving in concert to compete in the convergent spaces.
3. (Re-)Integration dynamics

The focus of this chapter is to determine the dynamics which drive (re-)integration of the PC platform and, in the process, answer the question: What are the forces affecting integration (or substitution) of PC peripherals? In other words, what determined the integration paths of the stand-alone peripherals?

Scope of study

The double-helix model specifies three forces that drive integration: technical advances, supplier market power and proprietary system profitability. This chapter examines these forces in detail – firstly from the perspective of the Utterback and Christensen models (using data from PC graphics/video subsystem), followed by a 6-forces analysis to determine plausible market forces. A model of the integration dynamics will then be proposed.

Utterback and Christensen analyses of the graphics/video subsystem

Evolution of the graphics/video subsystem

The video controller is like a “middle-man” between the CPU and the display. It translates what the CPU computes (with regards to graphical data) into a form which the display can show. Older video controllers were dumb in that they did only this translation – the CPU did all the processing. This was fine for older computing environment which used text-based outputs. However, with the advent of GUI-based operating systems, the amount of graphical data became too much for the CPU to handle. For example, whenever a window is moved, the positions of affected widgets (eg. frames, dialog boxes, cursors, scroll bars) have to be recalculated and then each pixel re-computed. The CPU would have quickly become a bottleneck if all the graphical calculation was left to it.

The first-generation 2D graphical accelerators were thus borne. Since the Windows operating system drove much of this need, the video controllers with 2D
acceleration became known as Windows accelerators. These controllers had dedicated hardware to handle the graphical processing needs of the Windows GUI. For example, when the operating system needs to move a window to a new position, the CPU only needs to re-compute the new window location and then sends an instruction to the video controller to “draw the window at this new location”. The video controller then takes over and the CPU can move on to more critical processes. From the time of the first 2D accelerators, the video controller effectively became a co-processor of the PC system.

Then came multimedia and a demand for 3D processing, largely driven by the gaming community. Similarly, if all the 3D computation (eg. calculating position of vertexes, applying textures to pixels) was left to the CPU, then it would quickly become overloaded. To take this load off the CPU, 3D accelerators were invented. The formative years (1995 to 1999) saw the competing companies toying with various architectures, features and designs (including a separate add-on card with only 3D acceleration hardware and no 2D capabilities). It was in 1998-1999 that a dominant design emerged. The dominant design comprised of a well-defined set of core hardware features (eg. transform and lighting acceleration, multiple texture mapping to a single pixel) supported by the two dominant 3D application programming interfaces – Direct3D from Microsoft and OpenGL. It was also at this time that the core processing unit of the video controller, which had grown to rival the CPU in power and complexity, became to be thereafter known as the GPU (graphical processing unit). For example, the processing unit of Nvidia’s FX5800 video controller boasts 130 million transistors,

---

59 Prior to 1999, there were the GLIDE and mini-OpenGL APIs, which were written specifically to support the proprietary 3D acceleration features on accelerators from 3dfx. Direct3D existed in a rudimentary and unstable form. As a result, most applications were released with GLIDE support. Unfortunately for 3dfx, Microsoft finally got DirectX correct in 1999 (with releases 6 and 7). The rest of the industry also came up with competent OpenGL support. The standards war was over - GLIDE and mini-OpenGL disappeared almost overnight (despite 3dfx’s attempt to make GLIDE open-source), and with them, 3dfx’s competitive advantage. 3dfx was acquired by Nvidia in 2000.
which is more than three times that of the Pentium 4 microprocessor (42 million transistors).

**Emergence of dominant design**

The Utterback model suggests that there is a boom in the number of participating firms in an industry’s infancy (i.e. the fluid phase), followed by an industry shake-out in the transitional phase once a dominant design emerges, during which the industry consolidates and the number of participating firms drops. In the case of the PC video controller industry, the fluid phase existed from 1991 (with the emergence of Windows accelerators) to 1998, when the dominant design emerged. Table 1 shows the number of chip-making firms in the industry from 1991 to 2002. Figure 11 shows this data in graphical form, and Figure 12 shows the market share (in terms of overall unit shipments) of the surviving firms in 2002.
Table 1: Chip-making firms in the PC video controller industry\(^{60}\).

<table>
<thead>
<tr>
<th>Year</th>
<th>Active firms in industry</th>
<th>Number of firms</th>
<th>Number of entrants</th>
<th>Number of exits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991 and before</td>
<td>Nvidia, ATI, Matrox, S3, Number Nine, Rendition, Cirrus Logic, 3DLabs, Trident, Tseng Labs, Oak Technology, Chips&amp;Technologies</td>
<td>12</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>1992</td>
<td>Nvidia, ATI, Matrox, S3, Number Nine, Rendition, Cirrus Logic, 3DLabs, Trident, Tseng Labs, Oak Technology, Chips&amp;Technologies</td>
<td>12</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1993</td>
<td>Nvidia, ATI, Matrox, S3, Number Nine, Rendition, Cirrus Logic, REAL3D, 3DLabs, Trident, Tseng Labs, Oak Technology, Neomagic, Chips&amp;Technologies</td>
<td>14</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>1994</td>
<td>Nvidia, ATI, Matrox, S3, Number Nine, Rendition, Cirrus Logic, REAL3D, 3DLabs, Trident, Tseng Labs, Oak Technology, Neomagic, Chips&amp;Technologies</td>
<td>14</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1995</td>
<td>Nvidia, ATI, Matrox, S3, Number Nine, Rendition, Cirrus Logic, REAL3D, 3DLabs, Trident, Tseng Labs, Oak Technology, Neomagic, Chips&amp;Technologies</td>
<td>14</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1996</td>
<td>Nvidia, ATI, Matrox, PowerVR, S3, Number Nine, Rendition, Cirrus Logic, REAL3D, 3DLabs, Trident, Tseng Labs, Oak Technology, Neomagic, Chips&amp;Technologies</td>
<td>15</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1997</td>
<td>3dfx, Nvidia, ATI, Matrox, PowerVR, S3, SIS, Number Nine, Rendition, Cirrus Logic, REAL3D, 3DLabs, Trident, Tseng Labs, Oak Technology, Neomagic, ArtX, Gigapixel, Chips&amp;Technologies</td>
<td>19</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>1998</td>
<td>3dfx, Nvidia, ATI, Matrox, PowerVR, S3, SIS, Number Nine, REAL3D, 3DLabs, Trident, Neomagic, ArtX, Gigapixel</td>
<td>14</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>1999</td>
<td>3dfx, Nvidia, ATI, Matrox, PowerVR, S3, SIS, Number Nine, Intel, REAL3D, 3DLabs, Trident, Neomagic, ArtX, Gigapixel</td>
<td>15</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>3dfx, Nvidia, ATI, Matrox, PowerVR, S3, SIS, Intel, Trident</td>
<td>9</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>2001</td>
<td>Nvidia, ATI, Matrox, PowerVR, S3, SIS, Intel, Trident</td>
<td>8</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2002</td>
<td>Nvidia, ATI, Matrox, PowerVR, VIA, SIS, Intel, Trident</td>
<td>8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2003</td>
<td>Nvidia, ATI, Matrox, VIA, SIS, Intel</td>
<td>6</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

\(^{60}\) Source: Various - company websites, cnet.com, news.com, and news releases from Mercury Research and Jon Peddie Research. Where possible, data was separately verified using the Hoovers business database. Note that the companies listed here represent the major players which had some degree of publicity. There are many more minor players who never appeared in the news — according to Jon Peddie Research, there were approximately 70 firms in the graphics chip business in 1995, and around 40 in 1998.

p. 45 of 112
Figure 11: Graphical plot of the data in Table 1.

Figure 12: Total graphics market share (in terms of overall unit shipments) in third quarter of 2002. (Source: Jon Peddie Research news release).
The data shown in Figure 11 conforms well to the Utterback model. As mentioned above, the fluid phase lasted until about 1998, when the dominant design emerged. In the fluid phase, entering firms (or entrants) outnumber exiting firms (or exits). As a result, the number of firms rose to an all-time high of 19 in 1997. The emergence of the aforementioned dominant design in 1998-1999 heralded a period of consolidation which saw numerous exits and almost no entrants. The data thus suggests that 1998-1999 marked the beginning of the transitional phase. As of end 2003, there were only 6 major players left in the industry. The relative market share of the big 6 in 3Q 2002 is as shown in Figure 12. The video controller chip industry is now arguably entering the specific phase – the consolidation seems to be nearly over. All survivors (with the exception of Matrox) are big companies with sufficient technical and financial clout to remain in the market. Matrox does seem to be on its way out – it has had poor sales and the lack of new products in its pipeline suggests that it is perhaps preparing to exit. Before I proceed to analyze the dynamics which give rise to this phenomenon, let us first look at the substitution threat posed by integrated graphics chipset.

**Attack from below by integrated video controllers**

The main reason why Intel has 23% (and growing) of the market share in Q2 2002, despite not having any discrete video controller products, is its dominance of the integrated video controllers or integrated graphics chipset (henceforth called IGC) market. To understand the substitution threat which discrete video controllers face from the IGCs, consider the evolution of performance shown in Figure 13. The chart shows the growth in performance of top-end discrete video controllers (from ATI and Nvidia, who are the undisputed market leaders) and IGCs, as well as the performance demanded in the various market tiers, from 1996 to end of 2003. Refer to Appendix A for the methodology employed in constructing this chart.
Figure 13: Performance evolution of discrete top-end video controllers and integrated graphics chipsets\(^{61}\).

The chart shows that, in terms of performance (which is the primary basis of competition), the discrete video controller is currently still in the Moore's Law-powered exponential section of its S-shaped growth (with perhaps a slight tapering-off in 2003). The trajectory of this phenomenal growth has taken the discrete video controller past the performance demanded by even the most demanding users (i.e. the top-end market tier). In fact, the rate of growth in

\(^{61}\) See Appendix A for the method employed to construct this chart.
performance is higher that the rate of increase in performance demanded in all market tiers.

This situation has left the lower market segments open to attack by a lower-performing alternative that is nevertheless competitive when judged on the next most important basis of competition. The attack has duly occurred – the attacker is the IGC, and although it loses out in performance to the discrete video controller, it triumphs handsomely on the basis of cost (and hence price). In other words, Christensen’s “attack-from-below” phenomenon has happened.

The chart also shows that the performance of IGCs exceeded the demand of the Business tier of users quite early on. When this happened, buyers switched their basis of selection from performance to price. The price of an IGC-based PC mainboard is significantly lower than a combination of a non-IGC mainboard and a low-end discrete video controller – the difference is usually the price of the separate discrete video controller.

The market for IGCs has quickly grown since 1998 (arguably the year when IGCs were accepted by the Business tier of users). In fact, this growth has fueled the overall expansion of the video controller market, as Figure 14 shows. The market for discrete video controllers seems to be saturated, as suggested by the general down-trend in shipments. The very fact that the IGC has achieved such impressive growth (apparently at the expense of discrete video controllers), despite having grossly lower performance, is sufficient proof that the basis of competition in the business tier has shifted to the secondary attribute of price. Since there are probably far more business/corporate users than any other, I expect the IGC shipments to keep growing as companies re-start their IT equipment replacement cycles due to the improving economy - Table 2 shows the growth rate of consumer and commercial PC shipments in the US from 2001 to 2004.
Figure 14: Shipment of video/graphics chips worldwide per year. (Source: Jon Peddie Research).

Table 2: Growth rate of consumer and commercial PC shipments in the US, 2001-2004.

<table>
<thead>
<tr>
<th>Year</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumer</td>
<td>-19.6%</td>
<td>8.5%</td>
<td>10.8%</td>
<td>13.5%</td>
</tr>
<tr>
<td>Commercial</td>
<td>-6.6%</td>
<td>0.5%</td>
<td>2.3%</td>
<td>9.0%</td>
</tr>
<tr>
<td>Total</td>
<td>-11.4%</td>
<td>3.2%</td>
<td>5.3%</td>
<td>10.7%</td>
</tr>
</tbody>
</table>

Note: *Forecast Data

The biggest winner of this situation is Intel. Intel has seen its market share in the video controller market grow to an impressive 23% in Q2 2002 almost exclusively due to its IGC shipments. Although its IGCs are not the best-performing\(^{62}\), Intel has aggressively leveraged on its market power to ensure that its PC OEM partners manufacture systems based exclusively on Intel IGCs (eg. Dell has no

\(^{62}\) Nvidia's IGCs currently have the best performance.
machines based on the Nvidia IGCs). As a result, Intel has the dominant market share in 2003’s IGC market (see Figure 15).

![Pie Chart]

Figure 15: Q3 2003 market share (in terms of overall unit shipments) of integrated graphics chipsets (IGCs). (Source: Mercury Research news release).

What all the above data suggests is that IGCs have successfully substituted discrete video controllers in the business tier. In other words, re-integration of the video controller is successful in the business tier. The obvious question to ask now is – would IGCs go on to penetrate all the other tiers in succession, starting with the low-end tier?

The answer to that question lies in the trajectories of the performance and demand growth as shown in Figure 13. The trajectory of the IGC’s performance looks like it is steeper than the growth in demand of the low-end tier. This suggests that the IGC will penetrate this tier very soon. When this happens, we will likely see a similar switching of selection basis from performance to price.

It looks like ATI and Nvidia are aware of this inevitable fact. Rather than adopt a posture of denial, they have actually taken the lead in hastening this event. They have IGC products in the pipeline with performances that will satisfy the low-end tier users, despite knowing that these products will cannibalize the sales of their
low-end discrete video controllers. They know that if they do not do this, some other company will. Low-end discrete video controllers will likely be successfully re-integrated onto the mainboard in 2005 or 2006.

However, the survival of mid-range and high-end video controllers is probably assured in the short-term. As it stands now, the demands of the mid-range and top-end tiers are growing faster than the rate of performance increase of the IGC. This suggests that the IGC will not be able to penetrate these two tiers for a good number of years.

But, it is important to note that the IGC is just in the infancy of its S-curve, and the initial trajectory is steeper than that of the discrete video controller. This suggests that the doubling time for the IGC will be shorter and the IGC will one day catch up, perhaps just when the discrete video controller hits the plateau of its S-curve. More importantly, this also means that the IGC will be successful in penetrating all market tiers in succession (assuming that the rates of growth in demand remain as they are).

So, barring de-integration forces provided by a disruptive or architectural innovation, the forces described above suggest a successful re-integration of the video controller onto the PC mainboard eventually. However, the PC industry is dynamic and, as mentioned in the introduction, the on-going “digital convergence” will affect the industry greatly. Future scenarios which might provide de-integrative forces will be described in the next chapter. For now, I shall continue to analyze re-integration by conducting a 6-forces analysis of the industry in order to determine (at least conceptually) other contributory market forces.
Market analysis using the 6-forces framework

A summary analysis of the PC industry using the 6-forces framework is shown in Figure 16. Only the factors pertinent to re-integration are considered. A more detailed description of the various factors follows.

**Competitors/Complementors**
- Industry has consolidated. 5 or 6 big players left. Finely balanced coopetition between leader Intel and the rest.
- Low barriers to exit.
- Re-integration as a means for Intel to:
  * Increase attractiveness of platform by driving down costs.
  * Defend its franchise as leader of PC platform.
  * Meet its revenue growth target in the face of falling PC prices and stagnating sales.

**Customers**
- Lengthening PC replacement cycles (from 3 to 5 years on average).
- Causes Intel and complementors to adopt strategy of pro-active obsolescence, which hinders re-integration.
- Synergies provided by re-integrated functionalities might set up virtuous cycle which promotes acceptance and hence re-integration.

The PC business

**Substitutes**
- Improving performance of integrated components (over discrete peripherals) increases substitution threat and hence re-integration possibility.
- Digital convergence poses a threat of functional substitution of the PC by some other device in the context of Home and Mobile computing. Intel might desire the increased flexibility and control through re-integration in order to better compete against new products.

**Suppliers**
- Threat of vertical integration by suppliers/complementors gives Intel the incentive to drive re-integration (in order to protect franchise).
- Risks associated with increased capital usage caused by vertical integration puts economic pressure against expansion and hence re-integration.

**New entrants**
- Digital convergence pits Intel and complementors against formidable competitors from Communications, Information and Consumer Electronics industry. From the angle of getting more flexibility in order to better compete, Intel has an incentive to drive re-integration.

Figure 16: 6-forces analysis of the PC business.
Competitors and Complementors

As pointed out in the above sections, the video controller chip industry has consolidated to a state whereby there are only a few major players left who have stable market shares. Ever-decreasing profit margins and high R&D expenses (to keep pace with the industry leaders) have forced many firms to exit the industry. Exits are facilitated by low barriers to exit (since exiting costs are low). The industry is highly competitive; although the surviving players compete across the product spectrum, each nevertheless dominates (or at least competes aggressively) in a particular product area.

For the PC industry as a whole, there is a fine balance between competition and cooperation\(^{63}\), since Intel is a complementor of all players (and vice versa) by virtue of being the leader of the PC platform. The demand of video controller chips (and indeed, any individual component of the PC platform) depends on the attractiveness of the platform. As the platform leader, Intel has to constantly juggle with decisions relating to the 4 levers framework in order to maintain or increase the PC’s attractiveness, whilst appropriating sufficient returns from the value chain.

The main forces which impact Intel’s decisions (on whether to integrate the video controller chip) can be generalized into three categories – attractiveness of PC platform, threat from major complementors/competitors (to its leadership position), and profitability. These forces are inter-related and there are inherent conflicts between them. This issue of inter-relatedness and conflicts will be explored later in this section – for now, a more detailed description of each force follows.

- **Attractiveness of PC platform.** The attack-from-below phenomenon described earlier suggests that Intel will move to integrate a peripheral like the video controller chip when continued innovation by a complementor

\(^{63}\) This balance between competition and cooperation has been termed “co-opetition” by Brandenburger and Nalebuff, who put the situation into the context of game theory. Further exposition of this topic is beyond the scope of this thesis – interested readers can refer to Adam M. Brandenburger and Barry J. Nalebuff, *Co-opetition*, New York: Doubleday, 1996.
does not contribute to the attractiveness of the platform. Intel entered the IGC market only in 1999-2000 even though, with its financial clout and competence, it could have entered way before that. A very plausible reason is that Intel realized the time had come when continued incremental innovation by the discrete video controller chip makers were not contributing to the attractiveness of the PC platform at the business tier (since the basis of selection had switched from performance to price). Its market-dominance strategy (as indicated by its IGC market share) suggests that Intel entered the market to stimulate demand and generate supply. Technological constraints aside, one might argue on the same basis that Intel still sees value in complementary innovation in the higher tiers and will therefore not make a move into these tiers just yet.

- **Threat from major complementors/competitors.** The “Intel-inside” strategy allowed Intel to displace IBM as the leader of the PC platform, so Intel has first-hand knowledge of the threat posed by a major complementor, especially one which supplies a critical component. VIA and SIS have launched their forays into the video controller market from positions of strength in the chipset market, whilst ATI and Nvidia are now moving into the chipset market as well. These growing spheres of influence pose a very real threat to Intel’s leadership position. Therefore, Intel might be re-integrating the video controller functionalities via the domination of the IGC market as a pre-emptive move to curtail the complementors’ growing influence. In this way, Intel protects its franchise by reducing uncertainties for itself, and thus maintains its hold on the leadership position. However, there is a danger that doing this might trigger a strong competitive response from the complementors.

- **Value-chain “appropriability”**. Intel’s platform leadership strategy up until the late 1990’s had been to concentrate on the microprocessor and
chipset businesses; it took a leading role in defining standards and then left complementary innovation to other firms\textsuperscript{64}. This strategy allowed Intel to maintain control over the hidden design parameters of the critical components of the modular PC architecture, and define or shape the visible design rules. However, Intel is a publicly traded corporation – the pressures to grow and extract more economic rents from the value chain might have caused Intel to start expanding vertically into related businesses. This consideration is made all the more plausible if one considers the falling prices of the PC (and its components - according to Michael Robertson (CEO of Lindows.com), the average PC price is falling at a rate of 20\% or more annually\textsuperscript{65}. The problem for Intel is that the prices of the microprocessor and chipset (ie. Intel’s core products in the PC market) are falling in tandem with the overall PC price. Therefore, Intel’s revenue from each PC sold is actually decreasing in absolute terms. To compound this problem, PC sales stagnated in the early years of the new millennium (see Table 2). Therefore, Intel was under considerable economic pressure to find avenues to maintain its revenues in absolute terms, and one logical extension of its business was to enter the video controller chip market (since chip design was, and is, Intel’s core strengths). According to Jon Peddie Research, about 3\% of Intel’s 1999 sales came from the video controller chip business, and this percentage would have grown substantially since (judging by the growth numbers displayed in Figure 14).

\textsuperscript{64} Gawer and Cusumano, \textit{Platform Leadership} (2002).

\textsuperscript{65} Further confirmation of this figure comes from IDC – the average PC price fell by 26\% from Nov 2002 to Nov 2003. Gartner says that the rate of reduction will slow down in 2004, however, as businesses and consumers start to buy PCs again - it predicts a price drop of only 4.5\% from 2003 to 2004.
In summary, the above arguments suggest that Intel might have strategic objectives (with regards to competition and complementary innovation) in driving re-integration, and these are:

- Increase the attractiveness of the PC platform by driving down costs through the re-integration of peripherals for which further complementary (incremental) innovation adds little value. The lowering of costs generates higher demand and hence higher sales for Intel.

- Defend its position as the leader of the PC platform. From this position of strength, Intel can dictate the evolution of the platform and hence maintain control over the demand for its microprocessors (which make up more than 50% of its sales). Intel knows of no other way to compete – being forced to compete on par with firms like AMD, Transmeta, Nvidia and ATI will mean that Intel has to drastically re-think and change its position with respect to the 4-levers framework. This eventuality will be a traumatic event from which Intel might never recover from.

- Meet its revenue growth target in the face of falling PC prices and stagnating PC sales.

**Customers**

There are two main interesting dynamics which concern customers – purchasing trends (relating to the PC product strategy and life-cycle) and synergies from integrated functionalities.

According PC World\textsuperscript{66}, the recent economic downturn had caused companies to stretch the active lives of their PC and laptops from a historical three-year average to four or even five years. This lengthening of replacement cycles pose a problem for Intel (and, indeed, Intel's competitors and complementors too) because sales will be affected. More generally, Intel and its complementors have

---

to counter the general inertia among consumers against PC upgrades or replacement once a purchase is made. This consideration is nothing new – the Intel-Microsoft partnership has been very successful in generating demand for ever-more powerful PCs through rapid software releases (eg. Microsoft has been averaging around 2-3 years for new OS releases). The Intel Architecture Lab is even charged with thinking up applications for more powerful PCs – in other words, Intel is actively pursuing a strategy of pro-active obsolescence.

The PC growth in the 80’s and 90’s was powered by waves of compelling (ie. killer) applications, which helped to boost demand for more powerful machines (eg. the GUI introduced with Windows 3.0, internet browsing, multimedia, productivity applications, desktop publishing, gaming etc.). The challenge for Intel and its partners now is therefore to find the source to drive the next wave of obsolescence.

That source is likely to be the new Windows 64-bit operating system (currently code-named Longhorn) and perhaps its accompanying slew of 64-bit applications. Longhorn boasts of a more sophisticated GUI which makes better use of 3D capabilities to provide a more compelling visual computing environment. The following text was provided by Microsoft to potential attendees of the Windows Hardware Engineering Conference 2003:

In the past, the OS desktop has been a single graphics surface, and each window was defined as a region on this shared surface. Each application was responsible for drawing to only its window regions of the shared surface. Visually, windows appear to overlap and usually only the front-most window at any pixel is actually drawn.

The Microsoft Windows Longhorn desktop is being drawn in a completely different way than all previous versions. Every window will have its own, full window-sized surface to draw to. The desktop will be dynamically composed many times a second from the contents of each window. The goal for desktop composition is to enable compelling new visual effects for both the Windows user interface and for applications created by third-party developers shown on increasingly affordable high-density displays.

This new GUI and other advanced features of Longhorn will require more processing power compared with, say, Windows XP’s features. This will perhaps
provide an incentive for PC purchases and/or replacements. Of more relevance to this thesis is the fact that the pursuit of pro-active obsolescence hinders or delays re-integration, because it increases the trajectory of performance demanded by consumers\textsuperscript{67}.

The strategy of pro-active obsolescence encounters tension from two other aspects of product strategy and life-cycle. The first aspect relates to what is perhaps the traditional strategy of market penetration and growth. The most effective mechanism to generate demand and penetrate more socio-economic layers is arguably to lower prices and make the product simpler. These are considerations which encourage re-integration. However, as the PC market becomes increasingly saturated, pro-active obsolescence will perhaps take precedence over market penetration and growth.

The second aspect relates to the stretching of a product's life-time in order to justify the huge up-front capital costs necessary in the semiconductor business. The industry refers to the escalating capital investments as Moore's second law – the text from an article in the Intel Technology Journal reads:

\begin{quote}
One of the great challenges ascribed to Moore's Law, that facility costs increase on a semi-log scale, is now known as Moore's Second Law. However, unlike his First Law, the industry would prefer to depart from Second Law predictions to avoid hugely expensive ($20 Billion) future fabs and attendant high chip costs\textsuperscript{68}.
\end{quote}

We can see from the above statement that there is a desire in Intel (and other players in the semiconductor industry to resist the semi-log escalation in capital costs. There is therefore an incentive for Intel to stretch the effective life-time of a product, and this provides resistance to the strategy of pro-active obsolescence.

The second point with respect to consumers is the synergies provided through integration of functionalities. The notebook is a case in point.

\textsuperscript{67} Recall from the earlier discussion on the Christensen model – forces for re-integration are stronger (and re-integration occurs faster) if there is a bigger difference between the trajectories of actual device performance and consumer demand.

The acceptance and popularity of notebooks has really taken off since the late 1990's – sales of notebook as a percentage of total PC sales in the US rose from 25% in Jan 2000 to 54% in May 2003\(^6\). Furthermore, Smith Barney predicts that notebook sales are projected to grow faster – 17% in 2004 versus 3% for desktops\(^7\). The main benefit of a notebook over a desktop is mobility - the determinants (or vectors) of mobility are nicely summarized in Intel's 10-K (ie. annual report) which was filed on 23 Feb 2004:

> Our strategy for the mobile platform is to deliver products optimized for some or all of the four mobility vectors: performance, battery life, form factor (the physical size and shape of a device) and wireless connectivity.

The attractiveness of a notebook therefore increases if it delivers better performance, lasts longer on a single charge, possesses a form factor which is appealing to the target market, and has seamless wireless connectivity. In recent years, the industry has come to realize that performance is no longer a primary basis of selection, and can therefore be sacrificed to boost the other 3 vectors. It is with this consideration that Intel released the Centrino notebooks in mid-2003, to great success. The first Centrino notebooks consumed less power, were lighter and more portable, and had built-in wireless network adaptors. Successive generations of Centrino notebooks have incorporated faster processors though.

There is therefore a strong incentive for Intel to re-integrate functionalities for notebooks – not only does it enable higher scores along the last 3 of the 4 mobility vectors, but there are also other synergies which arise from the re-integrated functionalities and these add up to further increase the attractiveness of the notebook. For example, lower power requirements give notebook designers several options to consider:

- Translate the power saving into a smaller battery and form factor.

---

\(^6\) Source: NPD Group (Jul 2003).
\(^7\) Source: Information Week, 24 Feb 03, p. 80.
• Translate the power saving into a brighter and higher-resolution LCD display.

• Translate the power saving into more integrated functionalities (e.g., GPS, webcam).

• Simply go with the existing battery and form factor (i.e., longer operating time with a single charge).

These synergies add to the notebook adoption momentum because the utility of the notebook is increased. The Centrino notebooks are already being used as portable media players since one can watch a complete DVD movie (or even two) on a single battery charge – airline passengers are frequently observed to do this. So, as the utility of the notebook is increased, more people will choose the notebook over the desktop. With more notebook users, the chances of finding more novel uses for the notebooks will be increased, thereby raising the utility of the notebook further. A virtuous cycle is therefore setup. Indeed, will this virtuous cycle for notebooks also mean a corresponding death spiral for desktops? Has the tipping point been crossed? Only time will tell.

Since the notebook is perhaps the epitome of a fully integrated PC platform, the notebook adoption momentum will (at least partly) translate into re-integration momentum.

Substitutes

There are two forms of substitution dynamics which affect re-integration in the PC platform. The first has already been discussed – discrete peripherals are subjected to the substitution threat posed by integrated components. I will not elaborate further on this issue here, other than to make the following generalization: when the performance delivered by an integrated subsystem grows at a faster rate than the performance expected by the target market (especially if the performance of the discrete subsystem exceeds the expected performance by a big margin), then the threat of re-integration becomes stronger.
The second form of substitution dynamics is that posed by functional substitution. One of the outcomes of digital convergence is that companies start to include extra functionalities into their products. Some of these added functionalities would invariably be traditional or core functionalities in other products. As a result, products from different categories start to compete against one another (at least at the periphery of the market space for the moment). One great example is the current battle right now between the PC, TV set-top box and video gaming machine.

The “digital home” is one of the more promising concepts to result from digital convergence. The whole concept revolves around the exchange of digital content (such as digital music, photo and video) among home electronic equipment via cable or home wireless networks\textsuperscript{71}. Microsoft’s vision and high-level strategy for the “eHome” is as follows:

\begin{quote}
Home life made easier, more convenient and more enjoyable with Windows. Consumer electronics and PC working together…. Breakthrough experiences through connected devices\textsuperscript{72}.
\end{quote}

This home network requires a hub (i.e. control center). It is no wonder that companies are now making the first moves to position their product concepts for this hub, since controlling this hub is akin to controlling the microprocessor in the PC platform.

From the quotes above, it is unsurprising that the concept from Microsoft and its major partners in the PC industry is unsurprisingly a PC acting as a media-center. This PC (which runs the Windows XP Media Center Edition operating system) takes over the functionalities of the hi-fi, set-top box, VCD/DVD player and the personal recording device – in short, it is what it claims to be, a fully-functional

\textsuperscript{71} There is even an industry consortium set up in 2003 to drive the required standards. Nearly all the major players are involved – Microsoft, Sony, Intel, HP, IBM, Fujitsu, Nokia, Philips, Samsung etc.

\textsuperscript{72} Source: Presentation slides of Cort Fritz, Lead Industry Strategist, Media and Entertainment, Microsoft (lunch talk in Sloan School, organized by the MIT Sloan MediaTech Club, on 9 Mar 04).
media player. On top of that, it is also a gaming device and provides all the
typical internet-related services (ie. email, browsing and video-conferencing) if
connected to the internet. Last but not least, it is a platform for delivering
broadband digital content for a truly interactive TV experience. With its inherent
processing power and intelligence provided by the OS, the PC stands a
reasonable chance of becoming the hub.

Competing concepts share the same vision, but differ in the avenue of attack.
Sony is coming in from the angle of the Playstation (ie. gaming device); media
and consumer electronics companies mostly promote the all-in-one set-top box
concept\textsuperscript{73}. Regardless of the differences, the underlying considerations of all the
competitors are similar – everyone realizes that with digital convergence,
competition has moved up in the nested hierarchy (see Figure 9) from the level of
the PC (or gaming device, or set-top box) to the level of the home network, of
which the control hub (be it the PC or otherwise) is simply a subsystem, albeit the
crucial and critical subsystem. Companies are now vying to control this important
asset even while they agree on standards for the visible design rules, so that they
can be in a position to become the architect (or platform leader) of the home
network in the future.

In order to have more flexibility and maneuverability to compete effectively in the
level of the home network, Intel will have incentives to re-integrate certain critical
subsystems. Re-integration gives Intel the ability to offer a homogenous PC
platform (or rather, a “PC subsystem” at the level of the home network platform)
for its partners and developers to build on\textsuperscript{74}, as well as the option to quickly adapt

\textsuperscript{73} Even within Microsoft, there are at least two business units with competing products to the PC-
based media-center – the XBox gaming device and a Windows-based set-top box. One can
interpret this apparent internal competition within Microsoft as a form of hedging risks and/or
blunting the threat from competitors.

\textsuperscript{74} A good parallel example is the XBox – Microsoft is keeping it a closed and fully-integrated
platform, and has no plans to open the architecture up whilst XBox is still building market share
against the PlayStation. This allows Microsoft to guarantee a homogenous platform for
developers.
the PC specifications (without having to coerce partners to move along) as needs change.

In short, the threat of functional substitution encourages re-integration because the benefits from control, lower uncertainty and flexibility over-ride the benefits from complementary innovation in this context.

**Suppliers**

The threat of vertical integration by key complementors/suppliers, and Intel's response, has been discussed earlier – recall that Intel might be using re-integration with the strategic objective of protecting its franchise in the face of increasing supplier power (in terms of mastery of the hidden design parameters of the critical core components of the PC platform, ie. the microprocessor and chipset).

The other main issue relating to suppliers (and Intel's threat of vertical integration) is also closely related to competitors and complementors – that of efficient use of capital. When a company expands vertically in the value chain and competes in a wider market with more products, it invariably uses more capital. There is a cost to using capital, as measured by the company-specific expected rate of return. Table 3 shows some financial data pertaining to Intel and companies in adjacent (or overlapping) parts of the PC or Home Network value chains which Intel might expand into. Interested readers can find more financial data on Intel in Appendix C.

---

75 Usually measured by the weighted average cost of capital (WACC).
Table 3: 2003 Financial data of Intel and companies in adjacent or overlapping parts of the PC or Home Network value chains.

<table>
<thead>
<tr>
<th>Company (Core business)</th>
<th>Revenue (USD millions)</th>
<th>Net Income</th>
<th>Net Profit Margin</th>
<th>Profit as % of assets</th>
<th>Profit as % of Shareholders' Equity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel (Microprocessor, chipset)</td>
<td>30,141</td>
<td>5,641</td>
<td>18.7%</td>
<td>12%</td>
<td>14.9%</td>
</tr>
<tr>
<td>NVidia (Graphics)</td>
<td>1,822.9</td>
<td>74.4</td>
<td>4.1%</td>
<td>4.6% *</td>
<td>8.0% *</td>
</tr>
<tr>
<td>ATI (Graphics)</td>
<td>1385.3</td>
<td>35.2</td>
<td>2.5%</td>
<td>3.2%</td>
<td>5.0%</td>
</tr>
<tr>
<td>Creative Technology (Audio/visual media)</td>
<td>701.8</td>
<td>23.4</td>
<td>3.3%</td>
<td>3.6%</td>
<td>5.5%</td>
</tr>
<tr>
<td>D-Link (Networking)</td>
<td>577.8</td>
<td>24.8</td>
<td>4.3%</td>
<td>4.6%</td>
<td>9.0%</td>
</tr>
<tr>
<td>Nitendo (Home gaming)</td>
<td>4,203.3</td>
<td>561.3</td>
<td>13.4%</td>
<td>6.2%</td>
<td>7.6%</td>
</tr>
<tr>
<td>Sega (Home gaming software)</td>
<td>1,645.6</td>
<td>25.5</td>
<td>1.5%</td>
<td>1.4%</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

Note: *2003 data was not available, so 2002 numbers were used as estimates.
Source: Hoover’s Online business database.

The last two columns of Table 3 (ie. the ROA and ROE) give an indication of the effectiveness with which capital was used by the companies in 2003. The numbers suggest that the adjacent portions of the PC or Home Network value chains are perhaps less profitable than Intel’s core business. If Intel decides to expand into these areas, then it will use more capital but achieve a lower rate of return. This economic concern is further exacerbated by digital convergence—the convergent spaces (in which the Home Network belongs) are still very fluid with respect to products and competition. Playing in these spaces is therefore more risky and the market will probably assign a higher risk premium to Intel. This will lead to a higher expected rate of return. So, making any moves which incurs
more capital without a rise in the actual rate of return might even destroy shareholder value!

Intel is therefore under some economic pressure to avoid making any moves which increases capital usage when its expected rate of return might go up\textsuperscript{76}. This consideration reduces the impetus to re-integrate and expand into neighboring parts of the value chain.

**New Entrants**

Intel is not only facing increased competition from its complementors, but also new competition in the form of powerful firms from other industries as digital convergence blurs the lines between the Computing, Consumer Electronics, Communication and Info-tainment industries. The Home Network arena mentioned earlier is but one example of a convergent space. Other spaces are also centered around the theme of ubiquitous computing (ie. connected anytime, anywhere, through any means). Examples include the vehicular computing/communication hub and the multifunctional personal digital device. Different companies and consortiums will have different visions of how these new-age devices should evolve. The impetus created here is that re-integration for the reasons already described.

In summary, the 6-forces analysis has revealed several interdependent forces that reinforce or counter re-integration. I shall now represent these forces using causal loop diagrams.

\textsuperscript{76} Of course, Intel might be willing to put up with increased capital usage and lower rates of return in the short term in order to meet the strategic objective of increased growth in the long term. This is the consideration behind Microsoft’s willingness to put up with the Xbox business, which incurred a $900M loss in 2003 (according to Cort Fritz, Lead Industry Strategist, Media and Entertainment, Microsoft).
**Model of re-integration dynamics**

The overall model which represents the considerations discussed above is shown in Figure 17. The model shows the complex inter-dependencies and tensions between all the factors previously mentioned. To facilitate interpretation, I have also broken down the model into 2 parts (Figures 18 and 19) which map nicely to the various sections of the 6-forces analysis.

---

**Figure 17:** System dynamics model (causal loop diagram) of factors impacting (re-)integration trends in the PC industry.
Figure 18: Dynamics which correspond to the 6-forces analysis on Complementors/Competitors and Suppliers.
Figure 19: Dynamics which correspond to the 6-forces analysis on Customers and Substitutes.

The dynamic model shows that forces for/against (re-)integration do not act in isolation and, indeed, some of the forces have contradicting effects. For example, the extent of digital convergence both increases and decreases the pressure to integrate. Finally, do note that the model is a greatly expanded version of the forces for integration as identified in the double-helix model.
4. More case studies – sound and communication subsystems

The audio and communication subsystems are arguably the other two PC subsystems (besides the video subsystem) which have been subjected to strong re-integration forces. This chapter presents three further case studies and brief analyses of integration in the PC platform involving the POTS modem, soundcard and network controller. It will be shown that the dynamic model developed in the previous chapter is sufficient to describe the integration paths of these three peripherals.

Scope of study

For each of the three peripherals, a brief history and background will be first provided, followed by a short analysis of the integration path according to the model developed in Chapter 3. I shall also discuss the unique situation with electro-mechanical devices.

Communication subsystem - the POTS modem

History and background

The POTS modem (henceforth referred to as just “modem”) is a device which enables communication between computers across the PSTN (Public Switched Telephone Network). The word “modem” is a combination of the words “modulation” and “demodulation”, which are the functions that a modem performs. The modem modulates digital signals from a sending computer into analog signals to be passed along the telephone line. At the receiving end, another modem demodulates the analog signals back into digital form so that the receiving computer can interpret them.
The evolution of the modem performance has been driven by the V.xx standards\textsuperscript{77} – Table 4 shows a summary of the more important standards. It can be seen that the modem performance (in terms of throughput measured by bits per second) steadily increased over a decade starting from the late 80’s. V.90 is perhaps the culmination of the modem’s incremental innovation, because the throughput has hit the theoretical maximum possible with the PSTN.

Table 4: Summary of V.xx modem standards.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Meaning</th>
<th>Date of standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>V.22</td>
<td>1200 bits per second duplex modem standardized for use in the general switched telephone network and on point-to-point 2-wire leased telephone-type circuits</td>
<td>Nov-88</td>
</tr>
<tr>
<td>V.22bis</td>
<td>2400 bits per second duplex modem using the frequency division technique standardized for use on the general switched telephone network and on point-to-point 2-wire leased telephone-type circuits</td>
<td>Nov-88</td>
</tr>
<tr>
<td>V.32bis</td>
<td>A duplex modem operating at data signalling rates of up to 14 400 bit/s for use on the general switched telephone network and on leased point-to-point 2-wire telephone-type circuits</td>
<td>Feb-91</td>
</tr>
<tr>
<td>V.34</td>
<td>A modem operating at data signalling rates of up to 33 600 bit/s for use on the general switched telephone network and on leased point-to-point 2-wire telephone-type circuits</td>
<td>Feb-98</td>
</tr>
<tr>
<td>V.90</td>
<td>A digital modem and analogue modem pair for use on the Public Switched Telephone Network (PSTN) at data signalling rates of up to 56 000 bit/s downstream and up to 33 600 bit/s upstream</td>
<td>Aug-98</td>
</tr>
</tbody>
</table>


Before 1998, the modem existed as either a stand-alone box (with serial or parallel connection with the PC) or an add-in PC card. In 1998, Intel made its first moves to integrate the modem onto the PC mainboard, via the AMR

\textsuperscript{77} The V.xx standards are driven and approved by the ITU (International Telecommunication Union) - a standards body based in Geneva, Switzerland. It is “an international organization within the UN System where governments and the private sector coordinate global telecom networks and services”.

p. 71 of 112
(Audio/Modem Riser) and MDC (Mobile Daughter Card) specifications. The rationale behind these two specifications was described in a Sep 1998 Intel press release:

**New Specifications Ease Audio/Modem Integration on to Motherboard to Reduce Cost and Ease Certification** .... Developed with a core group of industry leaders in audio, modem and PC manufacturing, the new modular specifications make integration of audio/modem functions on to the motherboard easier by separating the analog I/O functions to a riser card for the desktop platform, or a daughter card for mobile.... The AMR and MDC specifications also help reduce the baseline audio and modem implementation cost.... With a standard solution, the desktop system manufacturer can implement audio and/or modem solutions on the motherboard at lower cost... For mobile PCs, the MDC migrates audio and modem from the legacy ISA bus to the low cost AC’97 link, offering a low-cost and low-power solution. This makes the MDC ideally suited for basic and mini-notebook PCs, where cost and form factor are paramount.... Intel’s AMR and MDC specifications provide manufacturers added flexibility and speeds the cycle of delivering the latest technology to our customers.

The MDC had an immediate impact – a check of the PC World magazine archives from 1998 to 2000 revealed that around 2 in 10 notebooks had onboard V.90 modems in late 1998, around 50% in late 1999 and almost 100% from late 2000 onwards.

However, the AMR was not a success – the specification evolved into the CNR (Communication Networking Riser) and then the ACR (Advanced Communications Riser) before dropping off the radar by 2003. Standalone V.90 modems (including PCI add-in modem cards) still exist today – the sales are driven mainly by users who have no broadband access to the internet.

**Analysis of integration path**

The case of the POTS modem involves a few interesting dynamics. The strongest set of dynamics was perhaps the **R2 Value of complementary innovation** loop. Once V.90 emerged, there was nothing to be gained from

---

78 Strictly speaking, this statement is not exactly true – preceding the AMR/MDC specifications was the AC’97 specification introduced by Intel in mid 1990’s to eliminate legacy ISA support. The AMR/MDC specifications actually ride on AC’97. However, I will leave the discussion of AC’97 to the section on the audio subsystem where it is more pertinent.
complementary innovation because the throughput with V.90 had hit the theoretical maximum possible with the PSTN. Also, there was no performance difference between a discrete and integrated modem. The overriding consideration thus became the lowering of the PC price to further increase the attractiveness of the PC.

The fact that Intel developed the AMR and MDC specifications in collaboration with a core group of industry leaders (and left it to them to deliver the solutions) meant that Intel was sensitive to the effect of the *R1 Complementors’ competitive response* feedback loop. This arrangement ensured that there was minimum conflict with complementors and hence averted strong competitive responses.

It is also interesting to note that the AMR/MDC specifications did not lead to full integration – the specifications allowed complementors to deliver integrated solutions via add-in cards. This apparent compromise between discrete components and fully-integrated solutions was perhaps due to the strong balancing force caused by the *B4 Efficient use of capital* loop – maybe Intel was unwilling to enter into the relatively unprofitable modem (and sound) space.

The *R4 Synergies from integration* loop also entered into the equation, albeit weakly. The Intel press release revealed that a secondary objective was to provide manufacturers with added flexibility and hence speed up the cycle of delivering the latest technology to customers. Intel probably perceived some synergies arising from the integration.

In the end, the dynamics set in motion with the introduction of the AMR was not allowed to play out because of the appearance of broadband internet access in the early 2000’s, coupled with high-speed networking, was sufficiently disruptive to the modem business.

---

79 An AMR/CNR/ACR modem solution is not soldered onto the mainboard, but instead comes on a mini-card which is slotted into the AMR/CNR/ACR slot. It is still considered an integrated solution because it communicates directly with the chipset via internal buses.
**Audio subsystem – the soundcard**

**History and background**

The audio subsystem only really materialized in 1998 when Creative introduced the GameBlaster soundcard (which was the forerunner of the hugely successful Soundblaster line of soundcards) at the COMDEX computer trade show in Las Vegas. The debut was such a success that even Michael Jackson stopped by the Creative booth.

Since then, the PC audio capability has evolved beyond simple stereo sound output to today’s stunning environmental effects, powered by sound processors which rival the microprocessor in terms of complexity. In the mid-1990’s, Intel decided that the time was right to push for on-board audio and introduced the AC’97 specification to path the way for mainboards with integrated audio chips. The AC’97 is interesting in that it consists of two components – a digital controller (called the AC-link) which is built into the mainboard chipset and the AC’97 codec, which is the analogue component of the architecture. Intel drove AC’97 adoption via the AC’97 link and left the provision of the codec to complementors such as CMedia, Realtek and Creative.

The AC’97 integrated sound solution has lower performance compared to most stand-alone sound cards but is, of course, more cost-effective. Table 5 shows a chart comparing the attributes of an integrated audio solution with the Creative Soundblaster Augidy2 soundcard. To determine the market acceptance of integrated audio, it is instructive to look at the audio solutions of Dell’s PC offerings (as shown in Table 6).
Table 5: Comparison of integrated audio solution with the Creative Soundblaster Audigy2 soundcard.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Integrated audio solution (Realtek ALC650 codec)</th>
<th>Creative Audigy2 soundcard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound quality</td>
<td>95dB signal-to-noise ratio. 16-bit/48kHz encoding. 5.1 output channels. Affected by electrical interference from other mainboard components.</td>
<td>106dB signal-to-noise ratio. 24-bit/96kHz encoding. 6.1 output channels. Minimal electrical interference from other mainboard components.</td>
</tr>
<tr>
<td>Feature set</td>
<td>Limited. Uses microprocessor for audio processing.</td>
<td>Support for multiple DVD audio formats (THX, Dolby Digital etc.). Full EAX (environmental audio extensions) support for DirectX. Full hardware acceleration – no microprocessor loading.</td>
</tr>
<tr>
<td>Price</td>
<td>Est. &lt;$5 *</td>
<td>About $110</td>
</tr>
</tbody>
</table>

Note: * A low-end motherboard with the ALC650 codec costs around $50. It is unlikely that the codec chip contributes more than 10% of the cost.

Source: Product specifications on company website.

Table 6: Dell’s desktop PC offerings (March 2004).

<table>
<thead>
<tr>
<th>Model</th>
<th>Product description (target market)</th>
<th>Audio solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension XPS</td>
<td>The ultimate technology and design in a PC. Perfect for demanding multi-media such as intense gaming, video editing and large graphics files.</td>
<td>Creative Audigy 2 soundcard.</td>
</tr>
<tr>
<td>Dimension 8300</td>
<td>Cutting-edge graphics and processing power for competitive gamers and home business users.</td>
<td>Choice between: - Integrated 5.1 channel audio - Creative Soundblaster Live! soundcard - Creative Soundblaster Audigy2 soundcard</td>
</tr>
<tr>
<td>Dimension 2400</td>
<td>Perform every day computer functions with ease including productivity applications, email and entertainment.</td>
<td>Choice between: - Integrated 5.1 channel audio - Creative Soundblaster Live! soundcard</td>
</tr>
<tr>
<td>OptiPlex line</td>
<td>Business users</td>
<td>Integrated audio.</td>
</tr>
</tbody>
</table>

Note:

1. The Dimension 4600 was not included in the table because its target market was not distinctly specified – I would say the target market straddles those of the Dimension 8300 and Dimension 2400.

2. The Creative Soundblaster Live! card is a lower-performing predecessor of the Audigy2 card.

Source: Dell’s website.
The data in Table 6 indicates that the integration of audio capability is successful at the lowest tier (i.e. the business tier, which has least demands on sound processing power). The data also suggests that some users at the lower and mid-tiers (served by the Dimension 2400 and 8300 models respectively) find the integrated solution acceptable. It is only at the highest tier, in which demand for audio processing power is highest, that the soundcard is still currently free from substitution threat.

All notebook PCs, in which mobility is the chief concern, come with integrated audio.

**Analysis of integration path**

The integration trend with the audio subsystem is very similar to that of the graphics subsystem – a stand-alone soundcard facing an attack-from-below by a lower-performing integrated on-board substitute. Integration is already successful in the lowest customer tier and the notebook segment. Driving this integration is the strong **R2 Value of complementary innovation** and **R4 Synergies from integration loops**.

By splitting the AC'97 specification into two components (chipset and codec), Intel left room for complementary innovation. This suggests that the **R3 Value chain appropriability** loop was comprised to minimize the impact from the **R1 Complementor's competitive response** loop and also take into consideration the **B4 Efficient use of capital** loop.

The effect from the **B3 Pro-active obsolescence** loop is felt through the ever-increasing multimedia demands posed by digital convergence. For example, the audio subsystem of a media-center PC will be expected to process multiple theater-quality sound formats like THX and Dolby Digital. The required processing power is still beyond the capabilities of integrated audio, which causes a strong balancing force against integration.
**Communication subsystem – network controller**

**History and background**

The precursors of today's network architectures were the IBM's System Network Architecture (SNA) and Digital's network architecture, which both implemented time-sharing networks that used mainframes and attached terminals. LANs and WANs\(^{80}\) evolved around the PC revolution and make up nearly all networks today. In fact, the internet can be regarded as the biggest WAN currently in existence\(^{81}\).

There have been several implementations of LAN, in terms of both technology and topology. The most popular by far is the pairing of the Ethernet technology with the Bus topology (see Figure 20), which accounted for at least 86% of all network equipment shipments in 1997 and looks set to take over the entire market.

![LAN Bus/Backbone Diagram](Image)

**Figure 20: Bus network topology.**

The first official Ethernet standard (802.3) was released by IEEE in 1983. This first specification supports a 10Mbit/s transmission speed. As such, it is now called the 10BaseT Ethernet. Fast Ethernet was officially adopted in 1995 – it

---

\(^{80}\) LAN stands for Local Area Network. It provides a high-speed, fault-tolerant data network which covers a relatively small geographic area (eg. confined to a single building). WAN stands for Wide Area Network. WANs use thick-pipe transmission facilities to interconnect LANs.

\(^{81}\) Most of the background information on networks was taken from the PCTechGuide website.
supports a 100Mbit/s transmission speed and is known as 100BaseT Ethernet. The Gigabit Ethernet standard was officially ratified in 1999 – it supports up to 1000Mbit/s transmission speed (1000BaseT). There are further extensions to the 802.3 standard based on optical technologies with even faster transmission speeds.

The device which connects a PC, network printer or any Ethernet-capable machine to a LAN is the network controller, also called the NIC (network interface card). NICs started off as standalone ISA or PCI plug-in cards for PCs, and PCMCIA cards for notebooks. The AMR (or, to be more exact, CNR) initiative by Intel in the late 90’s appeared to kick-start the integration process. There was a half-hearted attempt by manufacturers to supply CNR-based NICs, but it quickly ran out of momentum. Instead, in late 2001 and early 2002, mainboards with integrated network controllers started to appear. Today, the integrated 10/100BaseT network controller is a standard feature of all mainboards. For notebooks, integration started a bit earlier in 2000/2001 and similarly, all notebooks today come with integrated 10/100BaseT network controllers. Therefore, integration of the 802.3 (10/100BaseT) controllers is successful.

In 1997, IEEE ratified the 802.11 specification (more popularly known as WIFI) as the standard for wireless LAN (WLAN). With 802.11, a wireless "station" (some device, usually a PC, equipped with a wireless NIC) can gain access to the LAN via an "access point". Figure 21 gives a graphical illustration.

\footnote{This is referred to as the "infrastructure" mode of 802.11. Nearly all corporate WLANs are based on this mode. There is an "ad hoc" mode for peer-to-peer communication. For the purpose of this thesis, I refer to the "infrastructure" mode whenever I talk about 802.11.}
The 1997 802.11 standard could support only up to a 2 Mbit/s data rate. This data rate was too slow to generate much interest or adoption. 802.11b was ratified in 1999. It supported up to a 11 Mbit/s data rate, and proved to be the spark which kick-started WLAN adoption – see Table 7 for WLAN adaptor shipments.

Table 7: Shipments of WLAN adaptors with PCs.

<table>
<thead>
<tr>
<th>Year</th>
<th>Units shipped with PCs (mil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>0.1</td>
</tr>
<tr>
<td>2001</td>
<td>0.5</td>
</tr>
<tr>
<td>2002</td>
<td>4.5</td>
</tr>
<tr>
<td>2003</td>
<td>6</td>
</tr>
<tr>
<td>2004</td>
<td>10.5*</td>
</tr>
<tr>
<td>2005</td>
<td>15*</td>
</tr>
<tr>
<td>AGR</td>
<td>172.41%</td>
</tr>
</tbody>
</table>

*Forecasted.
Source: Gartner (appeared in Network World, 19 May 03, p. 46).
The next update to the 802.11 standard was the 802.11g, which was ratified in 2003. It boosted the supported data rate to 54 Mbit/s\textsuperscript{83}. The 802.11n standard (which is expected to be approved in 2006 or later) will increase the data rate to 100 Mbit/s or more.

The wireless network controllers evolved in much the same way as the 802.3 controllers. For example, once the 802.11b standard was ratified, 802.11b controllers in the form of stand-alone NICs appeared. It was only in 2003 that 802.11b controllers started to become widely integrated onto the mainboard with the appearance of the (Intel-designed and driven) Centrino notebook platform. The same phenomenon has occurred with the 802.11g controllers. Stand-alone 802.11g appeared in 2003, with Intel announcing in Jan 2004 that it will start shipping the 802.11g integrated chip for the Centrino platform from the first quarter of 2004. Therefore, it looks like integration of the 802.11g controllers will follow the same path as that for 802.11b controllers. In fact, the 802.11b/g controllers look destined to join the 802.3 controllers as a standard feature of notebook PCs. Table 8 shows a Gartner forecast of the percentage of notebook PCs which will ship with WIFI controllers. In contrast, there seems to be little momentum in integrating WIFI controllers into desktop mainboards.

Table 8: Forecast percent of portable PCs which will ship with WIFI controllers.

<table>
<thead>
<tr>
<th>Year</th>
<th>Percent of mobile PCs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>10%</td>
</tr>
<tr>
<td>2004</td>
<td>31%</td>
</tr>
<tr>
<td>2007</td>
<td>68%</td>
</tr>
</tbody>
</table>

Source: Gartner (appeared in CRN, 17 Mar 03, p. 24).

\textsuperscript{83} The 802.11a standard was ratified at the same time as 802.11b. It supported a higher data rate (up to 54 Mbit/s), but operated at a higher (unlicensed) frequency band of around 5GHz. It also uses a different encoding method compared to 802.11b. Due to difficulties in developing 5GHz chips, 802.11a products only started to appear in late 2001, leading to low adoption. As such, the 802.11g (which uses the same encoding method and 2.4GHz band as 802.11b) is considered the true "successor" of 802.11b. Modern WIFI products usually support both a and g standards.
Analysis of integration path

For the 802.3 controller, it is interesting to note that the impetus for integration was not provided by the ratification of the original standard in 1983 nor the fast Ethernet standard in 1995. Integration only occurred in the early 2000’s. The trigger for integration was likely the appearance of broadband internet access. Within a few short years in the late 1990’s and early 2000’s, broadband access mechanisms such as the Digital Subscriber Line (DSL), cable and satellite technologies appeared. Table 8 shows the data speeds supported by the various 802.xx standards and the modems for the three broadband access mechanisms.

Table 9: Data speeds supported by the 802.xx standards and broadband modems

<table>
<thead>
<tr>
<th>Standard/Modem</th>
<th>Data speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.3 10BaseT</td>
<td>10 Mbit/s</td>
</tr>
<tr>
<td>Fast Ethernet</td>
<td>100 Mbit/s</td>
</tr>
<tr>
<td>Gigabit Ethernet</td>
<td>1000 Mbit/s</td>
</tr>
<tr>
<td>802.11b</td>
<td>11 Mbit/s</td>
</tr>
<tr>
<td>802.11g</td>
<td>54 Mbit/s</td>
</tr>
<tr>
<td>802.11n</td>
<td>100 (?))Mbit/s</td>
</tr>
<tr>
<td>ADSL</td>
<td>Download – 512 kbit/s, Upload – 128-256 kbit/s *</td>
</tr>
<tr>
<td>Satellite</td>
<td>Download – 500 kbit/s, Upload – 150 kbit/s *</td>
</tr>
<tr>
<td>Cable</td>
<td>Download – 500 kbit/s, Upload – 128-256 kbit/s *</td>
</tr>
</tbody>
</table>

* The figures quoted here are typical speeds. Actual speed depends on line quality, as well as caps set by service providers. ADSL stands for Asymmetric DSL, and is the most popular form of DSL.

Source: Various service provider websites.

Therefore, the main dynamics which featured most prominently in the initial stages of integration of 802.3 controllers came from the **R4 Synergies from integration loop**. The integrated controller simplified the process of connecting to the internet via broadband modems, which contributed to the expansion of the installed base and hence broadband adoption, and increased the probability of more broadband applications (eg. VoIP-based telephony) etc.
Once the **R4** loop got the integration dynamics running, other forces came into play. A major one was the **R2 Value of complementary innovation** loop. There was simply little value in complementary innovation since the fast Ethernet standard clearly specified the performance parameters. Therefore, it made sense for Intel to lower the cost of the PC platform by integrating the controller, which brought into play the **B2 Generate demand** loop. **R3 Value chain appropriability** was also a likely source of influence, since Intel might have foreseen that the network controller would become an integral part of the PC platform with the growth in internet – the potential revenue stream from shipping a controller chip with every PC sold provided a strong incentive for integration. **R1 Competitor’s competitive response** was likely a weak influence since Intel was already a direct competitor in the communication segment.

802.11b and 802.11g were ratified during times when people knew about broadband internet access. Therefore, the WIFI network controllers were quickly integrated into notebook PCs once the standards were approved. Driving this quick adoption were strong influences from the **R2, R3 and R4** loops as discussed above. Furthermore in notebook PCs, mobility considerations always provide additional strength to the **R4** loop – this was likely the main reason behind the rapid integration of the WIFI controller into notebook PCs. The **R4** loop is not as compelling in the desktop space, so integration of WIFI controllers into the desktop mainboard will take longer (if at all).

It is also interesting to analyze whether the 802.11x controller is disruptive (ie. poses a substitution threat) to the 802.3 controller. If one goes by the “attack-from-below” reasoning, then the situation looks ominous for the 802.3 controller. With the upcoming 802.11n standard, WIFI will support data speeds which are comparable to fast Ethernet. Even today, some companies (eg. US Robotics) are using proprietary extensions to the 802.11g standard to provide 802.11n performance. Once the performances of the 802.11g/n and fast Ethernet controllers are comparable, consumers will turn to other basis for selection. In this respect, WIFI has several advantages, but one major disadvantage. WIFI
enables easier and cheaper deployment of PCs (since there is no need for cabling), is easily scalable, and provides mobility advantages. However, the network integrity and security of a WIFI network is still in question – wireless networks are still prone to intrusion because the authentication mechanism is still in its infancy and consumers are still not knowledgeable enough about wireless security.

Therefore, it does seem that if the security concerns are addressed in the future, then WIFI will successfully disrupt and take over fast Ethernet as the de facto intra-LAN connection method. If that happens, then the 802.3 standard will “migrate” north-east and make a last stand with the gigabit Ethernet standard – there are networking spaces in which the higher data speed is valued (eg. in the “last-mile” connections and corporate LAN backbone). The cost of the gigabit controller is decreasing – in fact, a few manufacturers have announced that their next mainboard product will ship with an integrated gigabit Ethernet controller (eg. the NForce3 mainboard from Nvidia).

These three case studies have further illustrated that the dynamics affecting integration are complex and inter-dependent; it is insufficient to consider only one aspect of the dynamics.

**Caveat – electro-mechanical devices**

To conclude the discussion on integration, I have to note this caveat - not all subsystems can be easily integrated. The video, sound and communication subsystems were among the first to face integration because they are purely electronic in nature – to put it rather crudely, integration simply involved shifting electronic circuitry from the discrete stand-alone component to the PC mainboard. Integration becomes more difficult for peripherals which serve some electro-mechanical function. Examples of such peripherals include those involved in printing, sound production and man-machine interface. Although certain notebooks include some or all these functionalities in an integrated package, there is always a usability trade-off (eg. tinny notebook speakers with limited
audio range, exasperatingly small notebook keyboard) which creates a viable market for the discrete stand-alone peripheral.

However, advances in technology might yet render electro-mechanical devices obsolete by replacing them with virtual devices. An exciting example which has just been released is the virtual keyboard from iBiz Technology. The virtual keyboard is a laser-projection of a full-sized QWERTY keyboard onto a flat surface. Although the product currently exists as a standalone device, it is purely electronic in nature. Integration is but a step away. Also, one can easily imagine other MMI devices being replaced by virtual devices based on the same (or similar) technology.

Another electro-mechanical device which is under threat of obsolescence is the venerable Winchester hard-drive. With advances in flash memory progressing at an astounding pace, it is probably just a matter of time before the electro-mechanical Winchester hard-drive is effectively substituted by the purely electronic flash memory.

Printers will perhaps never be substituted as long as the world economy and society remain paper-based. The world as a whole has proved very resistant to any movement towards the concept of e-paper, much less towards a paperless society. However, advances in display technologies (eg. flexible/wearable LCD/OLED displays) will surely aid the paperless-society initiative. It is not impossible that decades from now, both paper and the electro-mechanical printer fade into history.

I can go on and on to describe other electro-mechanical devices and esoteric means of substituting them with purely electronic implementations – the most far-fetched of which is the replacement of the speaker/microphone with electrical

---

84 See company website [www.ibizcorp.com](http://www.ibizcorp.com)
85 Lexar has just released a 8GB compact flash card.
86 There are many other dynamics involved in the movement from a paper-based to a paperless society. For example, the currency system has to become purely electronic and access to the world-wide web has to be universal. It is an exciting area for further research.
signals sent to or received from the human nervous system! Further exploration of this topic is unfortunately outside the scope of this thesis. For now, it suffices for me to conclude that even though electro-mechanical devices are currently resistant to integration, the situation will perhaps not last for long.
5. Future of PC platform

Given the complex dynamics involved, it is not easy to predict the future of the PC platform. Nevertheless, it is informative to conduct a scenario analysis of the PC platform's future evolution based on the two most important (and uncertain) determinants\textsuperscript{87}. The time-frame of the analysis is the next 2 decades.

Scope of study

The methodology employed to partition the scenario space will be first explained. The four scenarios will then be presented.

Constructing the scenario space

There are multiple ways to partition the scenario space\textsuperscript{88}, but the one which I have chosen is based on the reach and range of the PC in the context of the nested hierarchy framework\textsuperscript{89}. Within this framework, the footprint of the PC can extend either sideways within an architectural layer (ie. increasing its reach), or upwards into higher architectural layer (ie. increasing its range). The key uncertainties which determine the PC's reach and range are the prospect of architectural innovation and extent of digital convergence respectively. Architectural innovation will allow the existing PC components to be re-configured in new ways (ie. a new architecture) within the same layer, whereas digital convergence will give the PC access to the higher layers.

\textsuperscript{87} This chapter is not meant to be a tutorial in Scenario Analysis. For further reading on this topic, refer to Bradley, Stephen P. and Richard L. Nolan, Sense and respond: Capturing value in the network era, HBS Press, 1998: Chapter 4.

\textsuperscript{88} Another logical way to partition the scenario space is to consider all the exogenous factors in the dynamic model.

\textsuperscript{89} The nested hierarchy framework was covered in Chapter 2. The reach and range concepts were adapted Keen (1991). See Keen, Peter G.W, Shaping the future: Business design through information technology, Harvard Business School Press, 1991.
Determinant 1: Prospect of architectural innovation

The PC can increase its reach by extending within an architectural layer. This will raise its utility by increasing the classes of devices it can connect to and exchange data (ie. the peripheral devices).

The existing PC architecture uses multiple fast buses for internal communication (ie. communication between the microprocessor, memory, storage, co-processing chips such as the sound and video processors etc.), and another set of external standards for communication with external peripherals. The two most common external standards today are the USB (for wired devices) and Bluetooth (for wireless devices). The chief constraint of this arrangement is that imposed by the paradigm of the PC box as a computing hub. With USB and Bluetooth, this constraint translates itself into a limited working distance.

Without an architectural innovation, this basic design paradigm and chief constraint will persist. Incremental innovation will no doubt slowly increase the PC’s reach by extending the device working distance from the PC box; however, only an architectural innovation can achieve a quantum jump in the PC’s reach.

The most likely architectural innovation on the cards is that offered by taking network computing to another level – imagine replacing all communication protocols of the PC (internal and external) with the Ethernet 802.x standard. The possibilities are staggering. For one, the PC components will no longer be confined to the PC box and can be diffused through the network (in effect, the network becomes the computer) - the look and feel of the PC (if it can still be called a PC) will be changed forever. It is an architectural innovation because it involves connecting up the PC components in new ways with minimum component-level changes. The chief constraint shifts from that imposed by a limited working distance from the PC box to network accessibility.⁹⁰

---

⁹⁰ Ideally, the network should be the internet, though one can easily imagine the concept confined to a self-sufficient standalone network like a corporate LAN.
This architectural innovation also enables an intelligent self-organizing network which assigns resources dynamically (and automatically) – in a way, the network constructs a virtual PC from the shared resources. Imagine the future personal computing device comprising of just a wearable display and a (well-hidden) wireless network adaptor. Despite the absence of a physical on-board computing engine, the device will be truly multi-functional because it relies on the network to marshal the needed resources. I shall leave further discussion of the implications to the scenario descriptions.

The technical challenges facing this architectural innovation are formidable, but not impossible. Table 10 shows the data rates of a few current PC internal/external communication standards. The data suggests that the WIFI standard (based on the 802.11n) needs to achieve a further 5x increase in data rate to match the speeds of the external PC communication standards (USB2.0 and Firewire), and a 100x increase to have a chance of replacing internal communication standards. Is this an insurmountable obstacle in this day and age? I think not, but only time will tell. Perhaps it is not even necessary for WIFI to replace all internal communication standards in order for architectural innovation to occur - the processing-heavy components can be tightly integrated and hosted by service providers. There are other possible forms of architectural innovation, but I shall assume the above for the purpose of the subsequent scenario analysis.

**Table 10: Data rates of some PC communication standards.**

<table>
<thead>
<tr>
<th>Standard</th>
<th>Data rate (Mbits/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCI</td>
<td>1056 (32bits at 33MHz)</td>
</tr>
<tr>
<td>PCI-X</td>
<td>8512 (64bits at 133MHz)</td>
</tr>
<tr>
<td>AGP</td>
<td>1066 (4x), 2133 (8x)</td>
</tr>
<tr>
<td>Serial ATA</td>
<td>1200 (or 150MByte/s)</td>
</tr>
<tr>
<td>USB 1.1</td>
<td>12</td>
</tr>
<tr>
<td>USB 2.0</td>
<td>480</td>
</tr>
<tr>
<td>Firewire (IEEE 1394)</td>
<td>400</td>
</tr>
</tbody>
</table>

*Source: Various manufacturer websites.*
Today, we are perhaps seeing the first steps of this architectural innovation – there are increasing numbers of peripherals based on the 802.11b/g standards. Examples include webcams (mostly employed as surveillance cameras) and music-streaming kits. However, these first-generation wireless peripherals are still tied to the paradigm of the PC box serving as a computing hub.

**Determinant 2: Extent of digital convergence**

The range of the PC is defined by its range of applications, i.e. how far it extends vertically in the nested hierarchy model. In today’s environment, the chief determinant of the range is arguably the extent of digital convergence. Will digital convergence gather pace and further blur the boundaries between the converging industries and their products? Or will digital convergence prove to be hype and stagnate in the near future? It will be interesting to investigate the possibilities in the scenarios.

A corollary of digital convergence is the convergence of the disparate data, voice, video and storage networks to an integrated IP network. Whether this integrated network will materialize and become the industry standard will depend on the extent of digital convergence.
Partitioning the scenario space

Based on the two key determinants, the four resulting scenarios are as shown in Figure 22.

![Diagram showing four scenarios based on two main determinants: Digital convergence stagnated, No architectural innovation, Architectural innovation occurred, and Digital convergence highly evolved.]

**Figure 22:** Four general scenarios based on two main determinants.

The impacts of the two main determinants can be graphically illustrated by plotting the range and reach of the PC in each of the four scenarios (see Figure 23). The plot shows that the PC is limited in both range and reach in Scenario 1, has better reach in Scenario 2 but still limited in range, does considerably better in Scenario 3 but not achieving full potential, and has maximum coverage (and hence highest degree of freedom) in Scenario 4.
Figure 23: Range and reach of the PC in the four scenarios.
Scenario 1: Plodding forward

If digital convergence stagnates in the near future, then Microsoft, Intel and all the major players in the PC industry will have very limited success in expanding the scope of the PC. Some lines will still exist between the traditional industries of computing, consumer electronics, communication and info-tainment. The functionality of the PC will be little changed and the range of devices which can connect to the PC to extend its utility (ie. the peripherals) will be pretty much as it is today.

The absence of architectural innovation will increase the likelihood of this outcome, since the paradigm of peripherals grouped around a computing hub (be it a desktop PC, notebook or PDA\textsuperscript{91}) places a limitation on the utility of the PC which might never be overcome. This scenario will be characterized by relentless incremental innovation in performance and form-factor design, resulting perhaps, on balance, a positive pressure on integration.

Thus crippled by the architectural constraint and inability to expand into other markets, the PC will remain limited to its existing architectural layer. At the very most, it will achieve a very tenuous foothold in a higher layer, eg. as a non-critical component of a home network.

For the aforementioned players in the PC industry, this scenario will mean that business strategies will remain focused on maintaining leadership within the PC layer and also ensure that the PC does not become a victim of functional substitution at the higher layers.

Given the current pace of convergence, this scenario is rather unlikely to occur. Using the eHome initiative again as an example –an earlier footnote mentioned that there is widespread coordination and collaboration between major players from the four converging industries through the auspices of an eHome industry

\textsuperscript{91} Note that all these are traditional computing devices in the sense that they have the same basic design consisting of a microprocessor, memory, storage etc.
consortium. It seems that the eHome vision, and a highly evolved digital convergence in general, is a distinct possibility. Scenarios 3 and 4 will cover this outcome.

**Scenario 2: Unrealized dream**

In this scenario, architectural innovation will occur to usher in the era of network computing. The PC (especially the core computation engines) “disappears" into the network in the sense that the components form a pool of common resources which can be dynamically assigned by the intelligent network\textsuperscript{92} according to user requests. In other words, we have a self-organizing network in which a virtual PC can be constructed from the common resource pool according to needs.

The network computer paradigm drastically extends the reach of the (virtual) PC. Any device which can connect to and be controlled by the network becomes a peripheral of the PC. Such peripherals are likely to be highly portable, specialized and stylized, since many former electronic components have moved into the network.

Despite its enormous potential reach, the utility of the PC in this scenario is unfortunately curtailed by its limited range. Digital convergence can stall for a number of reasons – lack of consumer interest, breakdown in cooperation between the companies currently driving the major initiatives (eg. eHome) etc. A stalled digital convergence will mean that hard barriers will come up between industries as companies strive to protect their own turf. Computing solutions will have a hard time crossing the industry boundaries. As such, the network computer will become a technical marvel with limited application. The look-and-

\textsuperscript{92} The network operating system is the heart and soul of the intelligent network. The company that controls the network operating system is likely to be the platform leader of the network computing era. Microsoft is well aware of this fact – even while it is busy making the Windows operating system ever more network-centric, it has quickly moved to curtail the influence of potential competition – the Netscape versus Internet Explorer episode is a good case in point. See Yoffie, David B. and Michael A. Cusumano, “Judo strategy: The competitive dynamics of internet time”, *Harvard Business Review*, Jan-Feb 1999: p. 71-81.
feel of the new-generation peripherals will be heavily tailored for the computing applications existing today.

The advent of the network computer will likely result in negative integration pressures. The focus will be firmly on increasing performance since the demand for shared resources will likely grow at a high rate. Also, de-integrated components increase the flexibility of the network (in terms of the degree of freedom in the marshaling of resources).

Business strategies in this scenario will again be constrained to the PC layer. There will be an initial race to establish the dominant “intelligent” network, after which the industry will settle down to some variant of the leader-competitor-complementor arrangement that we see today. How it actually pans out depends on the specific platform leadership strategy adopted by the winner.

This scenario is highly unlikely, because architectural innovation will likely contribute to the momentum of digital convergence.

**Scenario 3: Giant Leap**

If digital convergence lives up to its hype, barriers between the four converging industries will come crashing down and the PC gains extra range as it leaves the shackles of the computing industry. Also, all networks will converge to one which is IP-based and there will be an unprecedented ease of data sharing and transfer. Access to the internet will be ubiquitous. eHome will become a reality, as will other e-initiatives based on wireless connectivity centered around controlling hubs – for the purpose of this discussion, we shall assume that the PC will win the war and evolve into the preferred hubs of choice. These are the defining characteristics of the third scenario.

Incremental innovation of the PC platform will provide the technology for this next wave of digital revolution. Since the emphasis of this scenario is on the expanded range, innovation in form factor will likely be favored over innovation in performance. PCs will be highly specialized for their intended use – from the
multi-purpose home entertainment center to the ultra-portable personal computing device. However, the fantastic devices resulting from advances in form-factor technology will not disguise the fact that the PC architecture is basically unchanged. The fundamental tradeoff between usability and performance will still remain – the performance will depend on the number of transistors that can be packed into the form factor. In other words, performance will still be limited by the processing power which one can carry around. The utility of small form-factor PCs will be curtailed in this respect. Integration dynamics will be highly influenced by the usability-performance tradeoff.

The unchanged architecture will also mean that all PCs, regardless of their purpose and shape, serve as the hub for their own “local” network (e.g., the home entertainment center serves as the hub for the home network, the miniature personal computing device serves as the hub for the array of wearable wireless peripherals), as well as the access point to the internet (via some wireless base-station).

In this context, the business strategies of the players from the PC industry will surely be one of close collaboration to ensure that the PC becomes the platform of choice in the expanded range. If they succeed, one can expect the existing pattern of relationships in the PC industry to spillover into a larger context.

**Scenario 4: Computing utopia**

Finally, we come to the scenario in which both the PC’s range and reach are drastically increased. We will have the network computer from Scenario 2 coupled with the market penetration from Scenario 3 – a perfect fusion of technology and needs. Furthermore, synergies from having both increased reach and range will likely result in a wider coverage along both dimensions than any of the previous scenarios.

Devices will connect wirelessly to virtual PCs which are dynamically constructed out of shared resources according to needs. The usability-performance tradeoff will be broken since there will no longer be a need to carry your processing power
with you. Manufacturers will exploit this to come up with highly-specialized devices to meet the demands of a greatly-expanded market. The utility of the "PC" will surely be limited only by imagination.

This scenario will usher in the era of universal computing – access to information and processing power anytime, anywhere and through any device. Compare this to the (more limited) tenets of ubiquitous computing being preached today – access to information anytime, anywhere and through any device.

Integration dynamics and changes in business strategies are difficult to predict, since this scenario is such a major and fundamental shift from what exists today. It will be interesting to see how these pan out in light of radically new value-chain economics centered on a dynamically created virtual PC.

**Looking into the crystal ball**

The question which begs answering now is which of the four scenarios will come true. Although a definitive answer cannot be given, an educated guess can nevertheless be attempted by considering the various factors that determine the extent of digital convergence and the likelihood of architectural innovation.

The extent of digital convergence is arguably driven by three factors – industry collaboration, social acceptance and economics of implementation. The continuation of today’s burgeoning collaboration efforts between the major industry players is crucial, so as to maintain the momentum of digital convergence. Collaboration lowers the industry barriers and facilitates cross-market penetration, as well as the pooling of resources to work towards a common goal. A splintering of the coalition, on the other hand, will have the opposite effect – industry barriers will come back up with a vengeance and much resource will be wasted in pursuing conflicting goals. It is difficult to predict how market forces will drive collaboration, but the first steps currently being taken (eg. the setting up of the eHome consortium) suggest that collaboration will remain strong in the near future.
Social acceptance refers to the public’s willingness to change existing modes of behavior so as to embrace the new services that digital convergence brings. Since many of these services will be on-line and web-based, trust becomes a major consideration. Security measures must be put in place to give consumers a peace of mind to transact over the web. Fortunately, there is much R&D being conducted on network security now and the era of safe online transaction is perhaps not that far off. Another major determinant of social acceptance is the overall consumer satisfaction with the first-generation of on-line services, which affects the consumers’ willingness to conduct more involved on-line transactions. In this regard, the 34% growth rate of consumer spending on B2C e-commerce in 2002\(^{93}\) suggests that consumer satisfaction is likely to be high.

The economics of implementation perhaps provide the most significant barrier. There is still significant debate on the issue of who will pay for the all-encompassing network infrastructure – the industry, the government or the consumers? The economics will no doubt provide significant incentives which will affect industry collaboration and social acceptance one way or the other, so this barrier has to be overcome before digital convergence can become a reality. There is nevertheless at least one successful precedent – the i-mode infrastructure in Japan. In fact, the industry in Japan, spearheaded by NTT Docomo, is already implementing infrastructure for the next-generation ubiquitous computing applications. Also, the WIFI technology has the promise of enabling (relatively) low-cost infra-structural implementation, which will reduce this barrier considerably.

The likelihood of an architectural innovation of the type mentioned earlier depends on two factors – technology and (again) economics. Can wireless technology advance further after 802.11n, or does the 100Mbit/s mark represent the pinnacle of the 802.11 technology? From the viewpoint of physics, the

maximum achievable bandwidth with the 2.4GHz carrier signal is about 240Mbit/s (assuming a 10% usable bandwidth to avoid wide-band distortion problems) – this bandwidth is still too low to enable an architectural innovation. A higher-frequency carrier signal can be employed to increase the usable bandwidth, but doing so decreases the range. Even if the technological problems can be overcome, the economics is likely to pose an insurmountable obstacle. There is such an immense installed base of devices with the current architecture that the investments required to switch to a new architecture is very much prohibitive.

Therefore, if one believes that industry collaboration will continue and gather momentum, the public will embrace the new gadgets and on-line services, the infra-structure will somehow be paid for, wireless technology will provide sufficient bandwidth, but the installed base of devices with the current architecture provides too much of an inertia for change to occur, then digital convergence will evolve to a high degree but architectural innovation will not occur. This means that the base scenario (ie. the one most likely to happen) is Scenario 3: Giant Leap.
6. Conclusion

This thesis has examined the integration trends affecting the PC platform by analyzing real-life data and relevant market forces. Based on the analysis, a dynamic model of integration was proposed which contained the three main forces identified in the Double-Helix (i.e. technical advances, supplier power and proprietary system profitability). The model showed that the issues affecting integration are complex, and often inter-related. Nevertheless, the model proved adequate to explain the integration paths of several peripherals, which was one of the main motivations for this thesis.

The other main motivation was to consider possible evolutionary paths of the PC. For this purpose, a scenario analysis was employed. The reach and range of the PC were used a determinants to construct four scenarios. It was perhaps not surprising to find that the PC will derive most ubiquity and utility when both reach and range are maximized through architectural innovation and digital convergence respectively.

**Further research topics**

Based on the work presented in the above chapters, I propose the following areas for possible further research:

- Due to time constraints, the three mini-case studies in Chapter 4 were necessarily brief. The peripherals which were covered (especially the network controller) would make excellent choices for full-blown case studies.

- The dynamic model was limited to the level of causal-loop diagrams. An intrepid system modeler can take the next step and construct an operational model to test its accuracy.

- The replacement/substitution dynamics of electro-mechanical devices (as alluded to at the end of Chapter 4) are fascinating and worth an in-depth study.
• The value-chain economics of the four scenarios mentioned in Chapter 5 and the impact on business strategies are well worth a more detailed analysis. In particular, the study of the changes posed by the virtual computer (Scenario 4) will be fascinating.

• With respect to scenario analysis, other means of partitioning the scenario space (by using different determinants from the two I have chosen) can be investigated.

• Chapter 5 did not really touch on the role of complementary technologies (eg. advances in semi-conductor technology, open-source software) in shaping the range and reach of the PC – this topic will make an interesting study.
7. Appendices

Appendix A – Constructing the performance charts of video controllers

Measuring performance of video controllers

The pixel fill-rate (measured in pixels per second) and the memory bandwidth are the two oft-specified attributes of video controllers. However, they do not give an accurate measure of a video controller’s true performance in a real-life application. The pixel fill-rate theoretically measures the amount of pixels that can be rendered in a given amount of time. It determines the frame rate\(^4\) and resolution which the video controller can support. For example, a frame rate of 30 frames per second with a resolution of 1024x768 requires a minimum pixel fill rate of 23.6 mega-pixels per second\(^5\).

The video memory bandwidth reflects the amount of data which can be passed between the video processing unit and the video memory in any given time. It determines the resolution, color depth and refresh rate which the controller can support. It does not directly reflect the processing power of the controller, but it puts a limit on the controller’s performance – there is no point in having a fill-rate that can support higher resolutions if the memory bandwidth cannot keep up.

These two measures do not accurately reflect real-life performance because modern-day cards contain features which compensate for lower fill rates and memory bandwidths. For example, occlusion algorithms remove the need to render objects which are occluded, and hence enhance the “filling power” of the controller. Also, smart compression algorithms reduce the amount of data that needs to be transferred and hence lower the memory bandwidth requirements.

\(^4\) The minimum frame rate which is required to project an illusion of smooth motion is about 30 frames per second for the average person.

\(^5\) Each frame requires 1024x768 pixels. Therefore 30 frames per second require 1024x768x30=23.6 mega-pixels per second.
Real-life performance also depends on the hardware drivers – a badly-written driver will adversely affect performance.

As an example of the misleading nature of the pixel fill-rate numbers, consider the pixel fill-rates of two high-end controllers. The Nvidia GeForce FX5950 and ATI Radeon 9800XT have fill-rates quoted at 1900 Mpixels/second and 3300 Mpixels/second respectively. On paper, the ATI controller appears to be a superior product. However both controllers perform neck-and-neck when benchmarked in real-life applications. In any case, I have included the charts for pixel fill-rate, video memory bandwidth and transistor count of Nvidia's and ATI's top-end cards in Appendix B for readers who might want to look further into the numbers.

That brings me to the only reliable means of comparing video controllers - benchmark them in real-life applications. There exist quite a number of specially-written bench-marking programs. Many of these provide the frame-rates which are achievable under certain settings. Fortunately, there was no need for me to personally conduct the tests – many reputable websites regularly post results. I made use of data from two leading PC hardware review websites – www.anandtech.com and www.tomshardware.com. The credibility of these two websites is such that their reviews are referenced on the product web-pages of both ATi and Nvidia.

Selecting time frame and representative video controllers

I selected a time frame starting from the second half of 1996 (during which the first 2D/3D video controller from ATi appeared) to the end of 2003. The top-end controllers from ATi and Nvidia from this period are as shown in Table A.1. The table also shows the two top-performing IGs (integrated graphics chipsets) which I have selected as being indicative of the power of IGs.
Table A.1: Top-end discrete video controllers and integrated graphics chipsets from 1996 to 2003

<table>
<thead>
<tr>
<th>Year</th>
<th>Nvidia discrete video controllers</th>
<th>ATI discrete video controllers</th>
<th>Integrated graphics chipsets (IGCs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996 H2</td>
<td></td>
<td>3D Rage 2</td>
<td></td>
</tr>
<tr>
<td>1997 H1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1997 H2</td>
<td>Riva 128</td>
<td>3D Rage Pro</td>
<td></td>
</tr>
<tr>
<td>1998 H1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998 H2</td>
<td>Riva TNT</td>
<td>3D Rage 128</td>
<td></td>
</tr>
<tr>
<td>1999 H1</td>
<td>Riva TNT2 Ultra</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999 H2</td>
<td>GeForce DDR</td>
<td>3D Rage 128 Pro</td>
<td></td>
</tr>
<tr>
<td>2000 H1</td>
<td>GeForce 2 GTS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000 H2</td>
<td>GeForce 2 Pro</td>
<td>Radeon DDR</td>
<td></td>
</tr>
<tr>
<td>2001 H1</td>
<td>GeForce 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001 H2</td>
<td>GeForce 3 Ti-500</td>
<td>Radeon 8500</td>
<td>NForce</td>
</tr>
<tr>
<td>2002 H1</td>
<td>GeForce 4 Ti-4600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002 H2</td>
<td>GeForce FX5800</td>
<td>Radeon 9700 Pro</td>
<td></td>
</tr>
<tr>
<td>2003 H1</td>
<td>GeForce FX5900 Ultra</td>
<td></td>
<td>NForce 2</td>
</tr>
<tr>
<td>2003 H2</td>
<td>GeForce FX5950 Ultra</td>
<td>Radeon 9800 XT</td>
<td></td>
</tr>
</tbody>
</table>

**Normalizing performance numbers**

The problem with selecting such a long time-frame is that there is no one set of benchmark numbers which encompasses all the selected controllers. Therefore, I had to construct a consolidated set of performance numbers in a number of steps. The first step was to select a very recent set of benchmarks. This set was constructed from running the Unreal Tournament 2003 (Custom Inferno Timedemo) benchmarking program on an Intel Pentium 4 3.2GHz machine (with Intel i865PE motherboard, 1GB DDR400 RAM, and running WinXP with DirectX9.0b).
I then selected progressively older sets of benchmarking data in order to cover all the hardware listed in Table A.1. In the end, I had to use 7 sets of data (including the first set). I shall call these data-sets Benchmarks 1 to 7. The final step involved normalizing Benchmarks 2 to 7 using scaling factors calculated from the performance numbers of controllers which were featured in more than one set of benchmarks. For example, the scaling factor used for Benchmark 2 numbers was 0.56, which was calculated using the following steps:

\[
\text{Ratio of GeForce4 Ti4600 performance in Benchmark 1 to performance in Benchmark 2 = } \frac{65.8}{120.2} = 0.547
\]

\[
\text{Ratio of Radeon 8500 performance in Benchmark 1 to performance in Benchmark 2 = } \frac{39.8}{69.1} = 0.576
\]

Average of the above 2 ratios = 0.56

For the really old controllers (namely the Nvidia Riva 128, ATI 3D Rage2 and ATI 3D Rage Pro) for which no benchmark numbers are available, I simply scaled down the closest available normalized number according to the ratios of the fill-rates. For example, the normalized benchmark number for the Riva 128 was calculated by scaling the closest available normalized number (which happened to be that of the Riva TNT) by the ratios of the fill-rates of the 2 controllers.

Table A.2 shows all the 7 sets of benchmarks as well as the normalized set. Although this method of constructing a normalized set of benchmarks is admittedly not exactly accurate (eg. the older controllers will probably crash when forced to run the more modern benchmarking programs), the results are nevertheless representative of real-life performance across the ages.

---

\(^{96}\) Note that the setup (ie. software and hardware used) for Benchmarks 2 to 7 is not important due to the final step of normalization.
Table A.2: Benchmarks of the selected video controllers.

<table>
<thead>
<tr>
<th>Video controller</th>
<th>B/M 1*</th>
<th>B/M 2</th>
<th>B/M 3</th>
<th>B/M 4</th>
<th>B/M 5</th>
<th>B/M 6</th>
<th>B/M 7</th>
<th>Fill-rate**</th>
<th>Norm. B/M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riva 128</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>2.4</td>
</tr>
<tr>
<td>Riva TNT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
<td>4.3</td>
</tr>
<tr>
<td>Riva TNT2 Ultra</td>
<td></td>
<td>25.7</td>
<td>19.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>GeForce DDR</td>
<td></td>
<td>43</td>
<td>32.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16.3</td>
<td></td>
</tr>
<tr>
<td>GeForce 2 GTS</td>
<td></td>
<td>49.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18.9</td>
<td></td>
</tr>
<tr>
<td>GeForce 2 Pro</td>
<td></td>
<td>36.2</td>
<td>53.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20.3</td>
<td></td>
</tr>
<tr>
<td>GeForce 3</td>
<td></td>
<td>73.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40.9</td>
<td></td>
</tr>
<tr>
<td>GeForce 3 Ti-500</td>
<td></td>
<td>85.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>47.8</td>
<td></td>
</tr>
<tr>
<td>GeForce 4 Ti-4600</td>
<td>65.8</td>
<td>120.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>65.8</td>
<td></td>
</tr>
<tr>
<td>GeForce FX5800</td>
<td></td>
<td>85.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>85.1</td>
<td></td>
</tr>
<tr>
<td>GeForce FX5900 Ultra</td>
<td>105.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>105.4</td>
<td></td>
</tr>
<tr>
<td>GeForce FX5950 Ultra</td>
<td>108.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>108.7</td>
<td></td>
</tr>
<tr>
<td>3D Rage 2</td>
<td></td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>3D Rage Pro</td>
<td></td>
<td>75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>3D Rage 128</td>
<td></td>
<td>14.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>3D Rage 128 Pro</td>
<td></td>
<td>17</td>
<td>34.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>Radeon DDR</td>
<td></td>
<td>46.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>26.2</td>
<td></td>
</tr>
<tr>
<td>Radeon 8500</td>
<td></td>
<td>39.8</td>
<td>69.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>39.8</td>
<td></td>
</tr>
<tr>
<td>Radeon 9700 Pro</td>
<td></td>
<td>98</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>Radeon 9800 XT</td>
<td>114.2</td>
<td></td>
<td></td>
<td>170.5</td>
<td></td>
<td></td>
<td></td>
<td>114.2</td>
<td></td>
</tr>
<tr>
<td>Nforce</td>
<td></td>
<td>47.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18.9</td>
<td></td>
</tr>
<tr>
<td>Nforce 2</td>
<td></td>
<td>37.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24.7</td>
<td></td>
</tr>
</tbody>
</table>

* B/M = Benchmark. Benchmark numbers are in terms of frames per second.  
** Fill-rate numbers are in terms of mega-pixels per second.
Determining the market needs

The final step in constructing the performance charts was to determine the various tiers of customer needs and the growth in performance demanded in each of these tiers.

Based on their pricing strategies, ATI and Nvidia generally segment the market for (discrete) video controllers into 3 segments, which I shall call “low-end”, “mid-range” and “high-end” tiers. Besides these three tiers, there is also a tier for business users who have little or no need for 3D functionalities – I call this the “business” tier.

The current performance level expectation of the business tier is best captured by the video capability of Dell’s offering for the business customer – an Intel i865G integrated graphics chipset.

To determine the current needs of the “low-end” and “mid-range” tiers, I took the average performance of Nvidia’s and ATI’s controllers which are targeted at these tiers.

For the “top-end” tier, I chose the lowest-performing controllers from ATI’s and Nvidia’s top-end product families – these controllers are deemed to satisfy the needs of most (if not all) gamers.

Therefore, the current needs of the various tiers, based on the normalized performance benchmark described above, are shown in Table A.3.

Table A.3: Current performance needs of the video controller market.

<table>
<thead>
<tr>
<th>Market tier</th>
<th>Representative controller(s)</th>
<th>(Average) Normalized performance benchmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business</td>
<td>Intel i865G</td>
<td>9</td>
</tr>
<tr>
<td>Low-end</td>
<td>Nvidia FX5200, ATI Radeon 9200</td>
<td>31.5</td>
</tr>
<tr>
<td>Mid-range</td>
<td>Nvidia FX5700, ATI Radeon 9600</td>
<td>63</td>
</tr>
<tr>
<td>High-end</td>
<td>Nvidia FX5900, ATI Radeon 9800</td>
<td>96</td>
</tr>
</tbody>
</table>

Finally, to determine the trajectory of growth in performance needs in each tier, I drew a straight line between the current performance number (at the end of H2
2003) and the zero point at the start of H2 1996 (at which point the video capabilities really started to take off).
Appendix B – Other performance charts of video controllers

Figure B.1: Transistor count, pixel fill-rate and video memory bandwidth of top-end video controllers from ATI and Nvidia

p. 108 of 112
Appendix C – Intel’s financial data

<table>
<thead>
<tr>
<th>Income Statement</th>
<th>Dec 03</th>
<th>Dec 02</th>
<th>Dec 01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue</td>
<td>30,141.00</td>
<td>26,764.00</td>
<td>26,539.00</td>
</tr>
<tr>
<td>Gross Profit</td>
<td>21,863.00</td>
<td>18,114.00</td>
<td>17,183.00</td>
</tr>
<tr>
<td>Gross Profit Margin</td>
<td>72.50%</td>
<td>67.70%</td>
<td>64.70%</td>
</tr>
<tr>
<td>Total Net Income</td>
<td>5,641.00</td>
<td>3,117.00</td>
<td>1,291.00</td>
</tr>
<tr>
<td>Net Profit Margin</td>
<td>18.70%</td>
<td>11.60%</td>
<td>4.90%</td>
</tr>
<tr>
<td>Diluted EPS from Total Net Income ($)</td>
<td>0.85</td>
<td>0.46</td>
<td>0.19</td>
</tr>
<tr>
<td>Dividends per Share</td>
<td>0.08</td>
<td>0.1</td>
<td>0.08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Balance Sheet</th>
<th>Dec 03</th>
<th>Dec 02</th>
<th>Dec 01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Current Assets</td>
<td>22,882.00</td>
<td>18,925.00</td>
<td>17,633.00</td>
</tr>
<tr>
<td>Net Fixed Assets</td>
<td>16,661.00</td>
<td>17,847.00</td>
<td>18,121.00</td>
</tr>
<tr>
<td>Other Noncurrent Assets</td>
<td>7,600.00</td>
<td>7,452.00</td>
<td>8,641.00</td>
</tr>
<tr>
<td>Total Assets</td>
<td>47,143.00</td>
<td>44,224.00</td>
<td>44,395.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Liabilities and Shareholders' Equity</th>
<th>Dec 03</th>
<th>Dec 02</th>
<th>Dec 01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Current Liabilities</td>
<td>6,879.00</td>
<td>6,595.00</td>
<td>6,570.00</td>
</tr>
<tr>
<td>Long-Term Debt</td>
<td>936</td>
<td>929</td>
<td>1,050.00</td>
</tr>
<tr>
<td>Other Noncurrent Liabilities</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total Liabilities</td>
<td>9,297.00</td>
<td>8,756.00</td>
<td>8,565.00</td>
</tr>
<tr>
<td>Preferred Stock Equity</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Common Stock Equity</td>
<td>37,846.00</td>
<td>35,468.00</td>
<td>35,830.00</td>
</tr>
<tr>
<td>Total Equity</td>
<td>37,846.00</td>
<td>35,468.00</td>
<td>35,830.00</td>
</tr>
<tr>
<td>Shares Outstanding (mil.)</td>
<td>6,487.00</td>
<td>6,575.00</td>
<td>6,690.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cash Flow Statement</th>
<th>Dec 03</th>
<th>Dec 02</th>
<th>Dec 01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Operating Cash Flow</td>
<td>11,515.00</td>
<td>9,129.00</td>
<td>8,654.00</td>
</tr>
<tr>
<td>Net Investing Cash Flow</td>
<td>-7,090.00</td>
<td>-5,765.00</td>
<td>-195</td>
</tr>
<tr>
<td>Net Financing Cash Flow</td>
<td>-3,858.00</td>
<td>-3,930.00</td>
<td>-3,465.00</td>
</tr>
<tr>
<td>Net Change in Cash</td>
<td>567</td>
<td>-566</td>
<td>4,994.00</td>
</tr>
<tr>
<td>Depreciation &amp; Amortization</td>
<td>5,070.00</td>
<td>5,344.00</td>
<td>6,469.00</td>
</tr>
<tr>
<td>Capital Expenditures</td>
<td>-3,717.00</td>
<td>-4,760.00</td>
<td>-8,192.00</td>
</tr>
<tr>
<td>Cash Dividends Paid</td>
<td>-524</td>
<td>-533</td>
<td>-538</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>profitability</th>
<th>Company</th>
<th>Industry¹</th>
<th>Market²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Profit Margin</td>
<td>72.54%</td>
<td>63.97%</td>
<td>48.16%</td>
</tr>
<tr>
<td>Pre-Tax Profit Margin</td>
<td>24.69%</td>
<td>13.37%</td>
<td>6.81%</td>
</tr>
<tr>
<td>Net Profit Margin</td>
<td>18.72%</td>
<td>9.76%</td>
<td>3.94%</td>
</tr>
<tr>
<td>Return on Equity</td>
<td>14.90%</td>
<td>8.30%</td>
<td>7.70%</td>
</tr>
<tr>
<td>Return on Assets</td>
<td>12.00%</td>
<td>5.70%</td>
<td>1.30%</td>
</tr>
<tr>
<td>Return on Invested Capital</td>
<td>14.50%</td>
<td>7.20%</td>
<td>3.70%</td>
</tr>
</tbody>
</table>

Note: 1. Industry: Semiconductor-Broad Line.
       2. Public companies trading on the NYSE, ASE and NASDAQ.

Source: Hoovers online database.
8. Bibliography


