TECHNOLOGY CYCLES IN THE COMPUTER PERIPHERALS SECTOR: A TEST OF THE DEMAND HETEROGENEITY THEORY

by

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Abstract

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This study set out to test the claims of demand heterogeneity theory (Adner & Levinthal, 2001) regarding the dynamics of demand cycles in the personal computers graphics cards sector. The demand heterogeneity theory claims that technology firms continue to engage in product innovation in mature product classes and offer products featuring increasing performance at stable prices. Adner and Levinthal (2001) posit that the answer to this phenomenon lies in the demand context: technology that meets consumers' functionality and net utility thresholds leads to the emergence of technologically satisfied consumers. In the face of satiated technological needs, firms engage in product differentiation strategies and continued innovation due to fierce competition for technologically satisfied consumers. The consumers in turn enjoy additional functional benefits and luxurious bargains. The theory is based on mathematical modeling and remains empirically untested in the management science literature.

Acknowledgments

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1 Introduction

A central problem in technology innovation in the computer industry is identifying consumer demand cycles. Every year hi-tech consumer device producers must make decisions on what new functionality to release. When customers find new functionality attractive, demand can skyrocket and producers can price the product appropriately resulting in lucrative profits. But when customers reject the new functionality, demand falls and producers often suffer significant losses (from R&D and unsold inventory stocks). According to Schilling (2003) success of hi-tech products depends on multiple dimensions of value that customers derive from opting for the product. For example, customers who opt for the Apple I-Phone perceive or anticipate a value that exceeds the combined actual value of their present cellular telephone (Schilling, 2003; Suarez F. F., 2004). This perceived value is related to functional utility (the new functionality) of the I-Phone relative to the customer's existing cell phone. In addition to functional utility, the image associated with owning an Apple I-Phone –Apple's marketing efforts are geared towards transforming their technology products into status symbols- also contributes to the perceived value of the device. The problem of understanding and managing the dynamics of demand cycles for product functionality is persistent in many high-tech industries (cellular telephones, computer graphics, mobile music devices, computer games). However, while some theories have been proposed to explain dynamics of demand cycles and help with the management of hi-tech product releases, some still remain untested.

This research is informed by the theory of technology cycles, which focuses on the relationship between firms' strategic decision-making and technology evolution. A general claim of this theory is that firm-internal factors impact on the emergence of dominant designs as well as the extension of life-cycles. This research broadens the technology-cycles framework to include firm-external factors, such as those proposed by the organizational community support theory (Wade, 1995) and demand heterogeneity theory (Adner & Levinthal, 2001). The focus will be on the later theory which views technology evolution in light of the demand context in which technology is evaluated. While there has been considerable conceptual theory development in this area, theory testing has been neglected. Hence, this work will attempt to test the chief claims of demand heterogeneity theory (Adner & Levinthal, 2001) with respect to consumers' (demand-side) influence on technology evolution and firms' (supply-side) strategic responses in competitive high-tech markets.

1.1 Objectives of the Research

This master's thesis intends to contribute to our understanding of demand cycles dynamics for product functionality by empirically testing the *demand heterogeneity theory* of Adner and Levinthal, (2001). While most life cycle theories have explained the dominant logic of new product innovation and competitive strategy (Anderson & Tushman, 1990; Arthur, 1989; Katz & Shapiro, 1986; Klepper, 1996; Schilling, 1998), the link between innovation in mature products and competitive strategy was overlooked until Adner and Levinthal, (2001).

This study tests the predictions of demand heterogeneity theory against empirical data on the evolutionary development of AGP and PCIe graphics cards data bus architectures. In addition, there is an attempt to examine how the theory might explain the life-cycle extension of the older AGP architecture in the enthusiast graphics cards segment. The reason for choosing the personal computer graphics card sector is that it offers the possibility to empirically observe the dynamics of a fiercely competitive sector in which the competitors adopt different strategies (introducing new products and innovating on mature ones) to achieve competitive advantage. Four characteristics of this sector make it ideally suited for this investigation: (1) computer graphics cards demand is dependent on meeting customer functionality demand; (2) customers in this market segment are highly knowledgeable and share information with each other via online forums; (3) customers in this segment are likely to share their product evaluations with others thus offering a suitable source of data to study heterogeneous demand contexts; (4) computer graphics cards are the type of phenomena upon which theories of demand cycles apply.

1.2 Epistemological Orientation

This research applies the hypothetico-deductive approach to theory testing. It is rooted in the logical-positivist (and post-positivist) philosophy of science which is situated within the functionalist paradigm (Burrell & Morgan, 1979). The exact process of theory testing is illustrated in four steps depicted in Figure 1. From the perspective of this study this involves theory formulation, hypothesis generation, hypothesis testing, and presentation of finding (Palys, 2003).

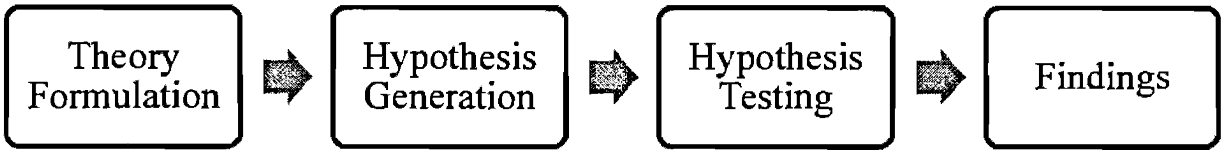

Figure 1: Hypothetico-Deductive Logic (Palys, 2003)

This approach constitutes the traditional top-down approach to scientific research in which an observed phenomenon (AGP life cycle extension) is examined in light of pre-formulated (demand heterogeneity) theory (Burrell & Morgan, 1979). (1) The researcher chooses from a range of suitable theories that may explain a particular phenomenon of interest and answer a research question. In the case that no suitable theories exist beforehand, researchers are free to suggest a theory on their own to explain observations. Researchers are also free to modify existing theories to that end. (2) The focus of the researcher working from this perspective is to generate testable hypothesis in accordance to the chosen theory's predictive claims. Hypothesis must include valid and measurable operationalizations of theoretical concepts and relationships. (3) The actual testing occurs through a number of different methodological tools available to researchers. Researchers are required to establish why their choice of testing methodology is suitable with respect to the data at hand and the underlying theoretical framework. In this particular study hypothesis testing is conducted via partial correlation and equality of means test procedures for the quantitative data. Text analysis in form of coding, categorizing and counting is applied to the qualitative data. These methods are elaborated in the 4.3 Data Analysis section in more detail. For hypotheses testing to be meaningful, hypotheses must be stated in a clear, unambiguous and falsifiable manner, meaning, criteria must be established ahead of time that determine whether there is enough evidence to support or reject a hypothesis. (4) The last step in the hypothetico-deductive cycle involves the presentation of findings. During the testing phase, researchers either established support for or rejected hypotheses. If theoretical claims stated in hypothesis form did not, or only partially reflected the data under observation, then the theory suggested in the first step is either abandoned or modified and the research cycle repeats. In any case (confirmation or refutation of theoretical claims), researchers must draw implications from their findings for the body of knowledge in their field of study. The major contributions to the body of knowledge in the management science literature with respect to technology evolution are discussed next.

2 Literature Review: Evolutionary Theory of Technology

This literature review focuses on the key theoretical concepts that form the foundation of the *Technology Cycles Framework.* This theoretical framework is rooted in evolutionary theory. According to Augier (2005), core assumptions, concepts and language of evolutionary theory have greatly influenced our understanding of technological development and management. Technology cycles theory concepts - diversity, selection, competition, adoption- borrow heavily from concepts of evolutionary theory. In general, evolutionary theory deals with developmental dynamics of behaviors, views, practices and artifacts. In evolutionary theory, diversity is viewed as inherent in nature and human experience. In the domain of human technological activity, such as the production of artifacts, it is human innovation that contributes to the pool of diverse technologies and technological processes. Selection processes discriminate between objects and procedures in the pool; some last for a short time, while others have a longer life-span. Finally, retention processes influence the longevity of technological artifacts and processes (McKelvey, 1997). The primary advantage of the evolutionary perspective is the classification and integration of developmental dynamics (emergence, development, extinction) of technology into one comprehensive framework. That is, the technology evolution framework breaks the problem into its constituent parts: innovation, selection, and retention (the last two are sometimes grouped together into selection-retention). Technological diversity is characteristic of the initial stage of the technology cycle. Subsequently, selection processes favor a given design and contribute to the emergence of a dominant design. Retention ensures the longevity of selected technologies, which may be due to lock-in effects (ex: emergence of complementarities, which are possibly independent of reasons for the emergence of the particular technology in question), the consumer demand context (as this research is about to examine), or other reasons.

The explanatory power of evolutionary theory, however, hinges on specifying the exact nature of selection-retention processes. For example, Darwin's original contribution to natural history –the concept of evolution predates him- was his specification of *natural selection of characteristics favorable to reproduction of organisms within a specific environment* as the driver of biological development. In the context of technology development, specifying precise selection processes still constitutes a significant research problem (Adner & Levinthal, 2001). Nevertheless, significant advances have been made in understanding technology evolution in terms of the technology cycles framework. The key ideas of the theory of technology cycles are discussed in the next section.

2.1 Key Concepts of the Theory of Technology Cycles

There are three key interrelated concepts upon which the theory of technology cycles is based. These are: (1) Network Externalities, (2) Design Dominance, and (3) Consumer Demand Context (Table 1).The concepts of the theory of technology cycles are discussed in terms of their basis of argument with reference to seminal papers where they appear. There are a number of discrete technology cycles arguments that are not exclusive to a single underlying theory and its theoretical concepts. These arguments interweave to form the basis to the three theoretical concepts within the different views in management of technology cycles literature. It is in that particular sense that the three concepts are considered interrelated.

THEORETICAL CONCEPTS	UNDERLYING THEORY	BASIS OF ARGUMENT	SEMINAL PAPERS
Network Externalities	Economic theory	Installed Base Complementarities Multiple Dimensions of Value Switching Costs Returns to Adoption Path Dependence Lock-in Effect	(Katz & Shapiro, 1986) (Schilling, 1999) (Arthur, 1989)
Design Dominance	Evolutionary theory	Multiple Dimensions of Value Complementarities Learning Curve Effects Network Externalities Bandwagon Phenomena Organizational Support Path Dependence Firm Capabilities	(Anderson & Tushman, 1990) (Suarez & Utterback, 1995) (Utterback & Abernathy, 1975) (Wade, 1995)
Consumer Demand Context	Marketing theory	Appropriability Opportunities Demand Heterogeneity	(Klepper, 1996) (Adner & Levinthal, 2001)

Table 1: Key Interrelated Concepts of the Theory of Technology Cycles

As Anderson and Tushman (1990) posit, technology change is cyclical: technological discontinuities usher an era of ferment characterized by uncertainty and turbulence; rapid improvement follows as firms engage in substitution and design competition to capture the majority of the market share; a domain design is selected and an era of incremental change follows along with market segmentation at different price points as well as diminishing returns; ultimately, a new technological discontinuity displaces the dominant design and the cycle repeats itself (Anderson & Tushman, 1990). Utterback, Abernathy and Suarez offer a similar model but use different terminology. Their technology evolution model recognizes two distinct phases; in the fluid phase there is uncertainty about the technology and markets –the technology is crude, unreliable and expensive; in the specific phase producers and consumers arrive at a consensus about the dominant design –producers shift their attention from product to process innovation (Utterback & Abernathy, 1975; Suarez & Utterback, 1995; Utterback & Suarez, 1993).

2.1.1 Network Externalities

Two theoretical arguments that can inform the theory of technology cycles are the economic arguments of network externalities and increasing returns to adoption.

Network externalities –also called positive consumption externalities- occur when users experience increases in value as the number of users of the same or similar product –the installed base- increases (Katz & Shapiro, 1986; Schilling, 1998; Thum, 1994). Network externalities suggest that the adoption of technology is not simply due to inherent properties of particular technologies. Koski, for example, presents evidence to show that the installed base, rather than some indigenous qualities of a particular technology explained the observed variation in the diffusion of microcomputers in the European market between 1989 and 1994 (Koski, 1999).

Along with technology's installed base, Schilling identifies the availability of complimentary goods and switching costs as other factors that determine the success or failure of technology. Complementary goods enable or enhance the value of another product or service. Self-reinforcing cycles ensue when products with a large installed base draw more complimentary goods on the market. Switching costs, on the other hand, constrain the selection of alternative products and technologies (Schilling, 1999). In fact, the production of complimentary goods, either directly or through coalitions offers an opportunity for firms to influence the selection of a dominant design (Wade, 1995). Schilling sums up the roles of installed base and complimentary goods in industries characterized by network externalities: these two factors combine with the stand-alone value of a technology to produce customer value. The stand-alone value -also referred to as technological utility- of technology, in turn, derives from its functionality, aesthetic qualities, and ease of use. However, new technology must not only surpass the functionality of incumbent technology, but also its' combined value in order to compete successfully (Schilling, 1999). That is, new technology can compete against the incumbent either by offering technological utility that exceeds all components of value of the incumbent (i.e. technological utility, installed base and complimentary goods), or by offering components of value that, put together, exceed the combined value of the incumbent. The value in excess of the combined value of the incumbent is referred to as marginal value of new technology (Schilling, 1999). Therefore, the extent of added marginal value of new technology greatly influences whether consumers will abandon the old design for the new one.

The increasing returns to adoption argument suggest that greater adoption leads to greater improvement of complex technology and to the development of specialized, complementary assets (Arthur, 1994). Arthur also suggests that increasing returns to adoption imply path dependent technology trajectories as well as mechanisms unrelated to technology's quality that influence the success or failure of technology (Arthur, 1989). This view in essence stretches the boundaries of mainstream economic arguments of supply and demand determining the adoption of technology. It is possible, as Arthur argues, that random historical events "lock-in" the trajectory of technology and thus exert great influence on technology cycles. The implication is that firms continue to invest in product and process innovation around a particular technology due to increasing returns. But, like the network externalities argument suggest, there also exist forces independent of "rational" attempts of firms to steer the technological path which reinforce technology cycles, not necessarily leading to efficient or predictable outcomes (Arthur, 1989). The next section discusses the basic concepts of dominant design.

2.1.2 Design Dominance

In addition to economic arguments of network externalities and increasing returns to adoption, three evolutionary arguments that also inform the theory of technology cycles are design dominance, bandwagon phenomena, and learning curve effects.

The notion of dominant design refers to a single product or process architecture that contributes to more than 50% of market share in a product category. Dominance of a design also depends on multiple dimensions of value that customers derive from opting for a technology. In addition, components of value can be actual, perceived or anticipated, which poses an additional hurdle for new technologies; even if a new technology exceeds the combined actual value of the incumbent, displacing the incumbent may still prove difficult if consumers ascribe the incumbent higher perceived or anticipated combined value (Schilling, 2003; Suarez F. F., 2004). The emergence of a dominant design is attributed to various internal pressures that industries experience, such as increasing returns to adoption and learning curve effects, as well as to network externalities (Schilling, 2007; Schilling, 1999).

The competition for design dominance is not simply between firms, but between technological communities supporting rivaling designs. While the existence and consequences of the bandwagon phenomena –path dependent adoption of technology– have been recognized in economic and organizational literature, processes that impact on support for specific designs and which start technological bandwagons have not been specified (Wade, 1995). In technological markets, communities of suppliers, producers and consumers play a significant role in shaping the competitive environment of firms. If we are to understand the selection drivers of technology evolution, we ought to understand its environment. Wade, for example, theorizes that technological communities shape the external environment with respect to individual firms by lending them organizational support for their technological designs. He also postulates that the evolution of technological communities sheds some light on the evolution of technologies (Wade, 1995).

The improvement of technology results from organizational learning and can be graphically represented in terms of learning curves, which relate cumulative production to variations in measures such as cost, productivity and performance (Argote, 1999; Hatch & Mowery, 1998; Schilling, Vidal, Ployhart, & Marangoni, 2003). In their study on organizational learning-by-doing in the semiconductor industry, Hatch and Mowery attribute learning curve effects to deliberate actions aimed at improving yields and reducing costs, rather than to simple increases in volume (Hatch & Mowery, 1998). However, Shilling et al point out that learning curve effects cannot be solely attributed to specialization (ex: focus on yield improvement and cost reduction efforts) either; they find that "related variation" (ex: related product/process innovation) produces higher organizational learning rates compared to task specialization alone (Schilling, Vidal, Ployhart, & Marangoni, 2003).

Again, what emerges from these arguments is the notion that technology selection is not solely dependent on inherent qualities of technological artifacts, but on a variety of firm-internal and environmental conditions in which technology is produced and evaluated. Firms learn to innovate and improve production processes; coalitions of suppliers and producers form for common economic benefit; consumers also form coalitions to select and support products that meet their task requirements.

In the present study, the two basic consumer communities under consideration include users of the old AGP legacy architecture and the users of the new PCIe architecture. It is hypothesized that these two communities exert an influence on add-in-board manufacturers' pricing and product strategies; that is, the first group is vying for continued support and product innovation around the legacy architecture, thus extending its life-cycle, while the second group is asking for new product functionality, performance increases and better compatibility for the new architecture. As the consumer demand perspective below suggests, and this study attempts to test, firms continue to engage in products innovation in both product categories so as to successfully create demand in both consumer groups.

2.1.3 Consumer Demand Context

I will now discuss the basic concepts of demand context which are also related to and supplement network externalities and design dominance arguments. Two arguments concerning consumer demand generally used to supplement the theory of technology cycles are scale appropriability and demand context. While patterns of product and process development throughout the technology life cycle are mainly attributed to the emergence of dominant designs, firm size related changes in appropriability opportunities also play an important role. As Klepper claims, incentives to pursue process innovations depend on the acquisition of new customers, rather than the installed base. Therefore, as markets mature, returns to product innovation tend to decline over time, providing added incentives for firms to switch from product to process innovation (Klepper, 1996).

However, Adner & Levinthal (2001) point out that the literature on technology evolution stresses the supply and neglects the demand side factors of technology cycles. In their view, the supply side of technology change essentially involves the evolution of firm capabilities. On the other hand, the demand based view of technology evolution focuses "on the interaction between technology development and the demand environment in which the technology is ultimately evaluated" (Adner & Levinthal, 2001).

For Adner & Levinthal a key assumption of dominant design and scale-appropriability arguments, which in their view cannot be generalized to all technologies, holds that there are lesser opportunities for product improvements in the later stages of the technology cycle. On the contrary, they point out continued innovation in mature product classes in large consumer electronics and computer industries. A key factor influencing later stage product improvements is customer demand. Henderson (1995) cites the example of the "unexpectedly long old age of optical photolithographic alignment technology" to suggest that the limits to a technology are not as predictable as supply perspectives of technology cycles would suggest. She observes how "unexpected changes in user needs and in the capabilities of component and complementary technologies permitted optical photolithography to dramatically exceed its 'natural' limits." She calls for better understanding of the social context of technology and its implications for technology evolution (Henderson, 1995). One key factor that has not yet been examined is the issue of increasing performance of technology at relatively stable prices (Adner & Levinthal, 2001). This is counter-intuitive to the supply side perspective which argues that firms improve on functionality to charge higher prices and gain market share, or abandon product innovation in favor of process innovation to reduce costs and increase margins.

The supply-side perspective of technology cycles theory and its various adaptations fail to account for the continued pursuit of technology improvement in mature product classes and their longevity. Supply-side theories predict a shift from product to process innovation, or the substitution of designs once diminishing returns set in at the end of the technology cycle. Adner & Levinthal, on the other hand, suggest that the observed continued improvement and longevity of technology can be understood in terms of the demand environment. A more encompassing understanding of technology evolution must include the demand context in which this process takes place, and the actors that shape the course of technology evolution.

3 Focus of the Study

The focus of this study is the demand perspective of technology cycles. The demand-based view suits this research objective better than the supply perspective, because it stresses firm-external factors. While the firm itself can exert influence on the adoption of a dominant design, anecdotal evidence suggests that the firm has far less control over the retention of a dominant design; i.e. how long will the incumbent technology dominate and what will bring about its demise. Again, a firm-external orientation offers analytical and explanatory utility for technology longevity questions that is certainly worth examining. An important question of interest to academics and business strategists is how does the incumbent design becomes obsolete or supplanted by another design in a competitive environment; more specifically: (1) Who or 'what' selects product designs that survive? (2) What are the dynamics of this selection-retention process?

One school of thought claims that the firm determines the dominant design via process innovation (supply side perspective) and the other claims that the customer determines the dominant design (demand side perspective). In other words, the supply perspective (i.e. technology cycles theory) asserts initial diversity –driven by product innovation- and the subsequent emergence of a dominant design at later stages –driven by process innovation- of technology evolution. Technology cycles theory, in particular, predicts that the emergence of a new dominant design (PCIe) will coincide with a decrease of innovative activity and improvement opportunities (performance, compatibility) for the design being displaced (AGP). Adner & Levinthal's demand side perspective, on the other hand, using evolutionary language, posits "locally adaptive behavior of firms in a heterogeneous demand environment" (Adner & Levinthal,

2001) and claims that continued performance enhancements in mature product classes are related to the demand environment in which technology is situated.

In their exhaustive review of literature on dominant designs, technological innovations and industrial change research, Murmann & Frenken enumerate and classify major contributions to the field by paper topic, level of analysis, product description, technology, market measures and other attributes (Murmann & Frenken, 2006). They confirm Adner & Levinthal as scholars offering alternative accounts to the causal role of dominant designs to explain changes in the nature of innovation and market structures (Adner & Levinthal, 2001). Although other competing perspectives have been used to study questions of technology cycles and design dominance and longevity, this study chooses to focus on Adner and Levinthal's contributions, which so far remain empirically untested.

In addition, Murmann & Frenken 's review enumerates product descriptions that were already addressed in the literature: automobile and automobile engines, video cassette recorders, cement kilns and control unit kilns, CPU's and memory, various glass machines, typewriters, TV sets and tubes, transistors, integrated circuits, electronic calculators, super-computers, photolithographic aligners, radio transmitters, hearing aids, chip architecture (Sun's Spark Chip), hard-disc drives, facsimile machines, mainframe CPU's, walkman, flight simulators, microprocessors (Intel based, PC and workstations), gas turbines, aircraft, helicopters, motorcycles, microcomputers, optical disks, local area networks and PC computers (Murmann & Frenken, 2006). Graphics cards are not present in this list nor did the literature review uncover this product category in the context of innovation research.

Finally, Murmann & Frenken call for standardization of terminology regarding various research aspects in the field (Murmann & Frenken, 2006). Table 2 reproduces their standardized system with the fields in the second column indicating how the research on the evolution of high-end computer graphics cards fits in. As a way of comparison, Murmann & Frenken's actual overview of research in the field is reproduced in Appendix I.

Topic of Paper	Consumer level support and demand context factors in the selection of dominant designs and the extension of technology cycles
Level of Analysis	Subsystem
Product Description	Graphics Card
Nature of Technology	Component of system
Technological Context	Personal computers
Technology Measure	GPU and memory speed, memory bandwidth
Market Share Measure	n/a
Level of Standard	Architecture of subsystems (bus architecture)
Description of Standard	AGP versus PCIe based GPU's
DD (Yes, No)	Yes
Mechanism Creating DD	Consumer support, demand context, network externalities
Critical Dimensions of Success	Speed, cost, compatibility, functionality, customer satisfaction
Difference from Earlier or Alternative Designs	Performance, compatibility

Table 2: The Study of the Evolution of high-end Computer Graphics Cards and how it fits within Murmann & Frenken's Framework for Research on Dominant Designs, Technological Innovation and Industrial Change (Murmann & Frenken, 2006)

3.1 Theoretical Framework for the Research

The theoretical framework of this research is the demand heterogeneity theory of Adner and Levinthal (2001) which seeks to explain patterns of technology evolution in the latter stages of product life cycles (Figure 2). More precisely, the demand heterogeneity theory claims that firms (C1) continue to engage in product innovation and (C2) offer products with increasing performance at stable prices. Adner and Levinthal (2001) posit that the answer to this phenomenon lies in the demand context: technology meets consumers' (C3) functionality and (C4) net utility thresholds, which produce (C5) technologically satisfied consumers. In the face of satiated technological needs, firms engage in product differentiation strategies and thus continued innovation due to fierce competition for technologically satisfied consumers. The consumers in turn enjoy additional (C6) functional benefits and (C7) luxurious bargains.

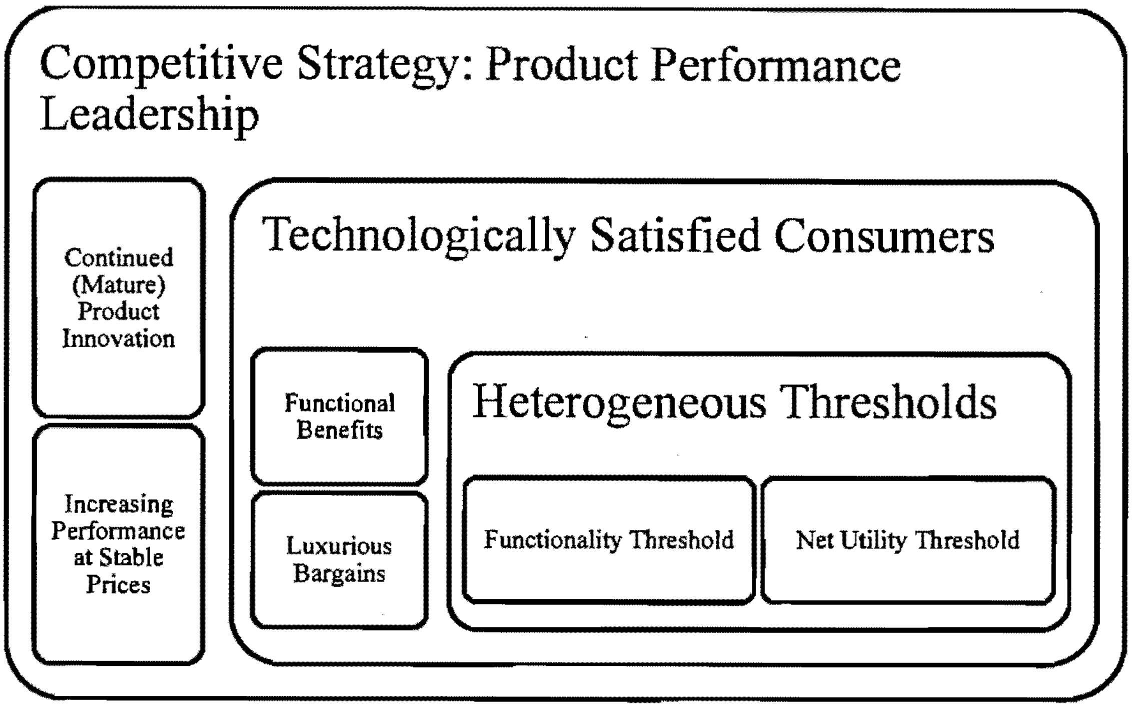

Figure 2: Theory of Demand Heterogeneity (Adner & Levinthal, 2001)

Adner and Levinthal's demand heterogeneity theory contradicts the technology cycles theory which predicts that the emergence of a new dominant design (PCIe) will coincide with a decrease of innovative activity and improvement opportunities for the design being displaced (AGP). Adner & Levinthal, on the other hand, claim that continued performance enhancements in mature product classes exist and are impacted by the demand environment in which technology is situated. In arguing for their competing theory Adner and Levinthal state:

> *"Viewing the evolution of technology through a demand-based lens suggests that the early evolution of technologies is guided by responding to the unsatisfied needs of the market. After sufficient development, however, firms face the intriguing possibility that these guiding needs have largely been satisfied. The framework developed here suggests that product maturity may be as much a function of satiated needs as it is of exhausted technologies. Mature consumer demand for performance in the face of unexhausted development trajectories places firms in the difficult position of needing to differentiate their offerings from those of their rivals, but of doing so for a consumer pool whose appreciation of performance improvements will not be reflected in their willingness to pay for the improved product. The competitive dynamics illustrated for the monopoly case, in which the monopolist ceases innovation at the point of demand maturity, illustrates the challenge posed by competition in the face of mature demand"* (Adner & Levinthal, 2001).

While the demand heterogeneity theory is elegant and compelling, its basic claims have not been empirically tested. The primary objective this thesis is to test the basic claims of the demand heterogeneity theory against evidence from the evolutionary development of high-end graphics cards. Figure 2 provides an overview of the key elements of the theory that will be interrogated in this empirical analysis. In the next section I will outline the key concepts of this theory and the framework for empirical analysis.

3.2 Key Concepts and Definitions

Adner and Levinthal (2001) based their demand heterogeneity theory on the idea that firms continue to innovate on mature products providing increasing performance at stable prices, provided there are technologically satisfied consumers. They argue that when competing against new products firms that appropriate product functionality, net utility thresholds, and stable prices can produce demand for competing mature products, and thus create functional benefits, luxurious bargains that lead to technologically satisfied consumers. The central argument of the *demand heterogeneity theory* is that consumer demand for specific technologies is shaped by a set of consumer preference thresholds. These thresholds are consumer-specific; they differ between individual consumers and are thus heterogeneous. Whether a product meets or exceeds these thresholds impacts on consumer's decision to purchase or not to purchase a given product.

I will now define the key concepts of the theory that will need to be operationalized for later testing; (1) technologically satisfied consumers, (2) consumers' functionality threshold, (3) consumers' net utility thresholds, (4) functional benefits, (5) luxurious bargains, and (6) increasing performance at stable prices.

The notion of *technologically satisfied consumers* is contrary to the commonly held view that the evolution of technology is solely driven by ever-increasing needs and functional requirements of consumers. The later view somehow holds that technology struggles to keep up with expanding societal needs and that product innovation of firms is largely dictated by efforts to develop new products that will meet those needs. Adner & Levinthal assume that consumers' basic functional needs are fairly constant over time (Adner & Levinthal, 2001). Technologically satisfied consumers, then, are those consumers that have their functional needs met. Assumption of constant *needs* is not to be confused with constant *wants*. A simple cell phone will readily satisfy the fairly constant need to communicate with others while not being tied to a landline. The addition of a photo camera, mp3 player, and an elegant interface to a cell phone is certainly welcome, but these extras will not sway the consumer to purchase a fancy cell phone at any price. Therefore, Adner and Levinthal expand the notion of technologically satisfied consumers to consumers that have their functional needs met at a price they are willing to pay. That is, consumers are technologically satisfied if technology meets their functional *and* net utility thresholds.

In fairness, there are many technological problems that have yet to be solved, say, alternative energy generation or environmental pollution control needs. However, in the context of the multi-billion dollar consumer electronics industry and especially personal computers industry, technological products often feature functionality and performance far in excess of real consumer requirements. Consider, for example, a video card that runs popular computer games at refresh rates in excess of 100 FPS (frames-per-second), when 40-50 FPS would be more than sufficient to rid the game of "choppiness" and make it playable. In comparison, feature presentations in movie theaters have a refresh rate of 24 FPS, while television sports videos usually refresh at 60 FPS, showing fast motions of a tennis match with life-like realism and detail. While some LCD television sets, for example, still have problems with 60 FPS refresh rates, most cathode ray (CT) television sets do not have this problem. Consumers that are conscious of that fact, either through direct experience or by reading product evaluations of other consumers, and require fluid refresh rates at 60FPS, will not be technologically satisfied with a LCD set. If such a LCD set demands higher prices compared to a CT set, our hypothetical consumer will be even less satisfied. On the other hand, another consumer may not care for 60FPS refresh rates at all, but may care for the combined value of a LCD set instead (i.e. screen size, aesthetic characteristics, compact design allowing wall mounts, or the fact that neighbors and friends also own LCD sets). The two hypothetical consumers have thus differing functional requirements; that is why Adner and Levinthal refer to heterogeneous thresholds. In summary, consumers' functional thresholds differ from individual to individual, but are assumed constant over time to any particular individual. Technology needs to exceed consumers' functional thresholds to be satisfactory. On the other hand, competing technology needs to offer greater combined value at a price consumers are willing to pay to overcome the functional value of the incumbent. The combination of functional and net utility thresholds, in Adner and Levinthal's view, greatly influences the emergence of technologically satisfied consumers and thus the adoption of technology.

Consumer's functionality threshold refers to the minimum performance requirements that a given product has to meet or exceed in order to be selected for purchase. The functionality threshold is determined by *the inherent task requirement* and *context* of a given product. In the context of AIB graphics cards, for example, the product under consideration has to be compatible with the consumer's existing hardware and software environment, it has to fit, install, and boot-up properly, and most importantly, it has to enable the consumer to run applications and games at screen refresh frame rates that are subjectively deemed appropriate by the consumer. Further factors that complicate this picture and are vital to this research include the performance stability, acoustic noise, and generated heat temperatures that influence a consumer's assessment of whether a given AIB card meets consumers' functionality threshold.

Consumer's net utility threshold refers to the "highest price consumers are willing to pay for products that meet minimum performance requirements." The net utility threshold "captures the interaction of product performance and price", and "allows for considerations of technology improvements in both, performance and price" (Adner & Levinthal, 2001).

Functional benefit refers to the "functionality offered by a product in excess of the consumer's minimum functionality threshold (Adner & Levinthal, 2001)" A consumer may select a product that exceeds her minimum performance requirements over a product that verifiably just meets it if the price differential between competing products is not too great. This situation occurs quite often in the context of AIB graphics cards. Namely, certain products lend themselves to GPU and memory over-clocking better than others. In effect, a consumer selects a product that verifiably meets the functionality threshold according to the marketed product description, but the decision to purchase that particular product is galvanized if the product is known to over-clock well, that is, if the product verifiably offers additional functional benefits. Such information is often contained in user generated product feedback located on merchant web-sites as well on review web-sites dedicated to GPUs, CPUs and PC motherboards. A whole branch of review web-sites has sprung up in recent years with the sole purpose to evaluate how far PC components can be pushed in excess of their inherent design requirements, that is, how much functional benefit does a given product offer to consumers. Adner and Levinthal posit that "the potential for technological progress remains unexhausted even after the population's willingness to pay for improvement is largely exhausted" (Adner & Levinthal, 2001). For example, the emergence of *luxurious bargains* captures "the dynamics of technology development when exogenous limits to development are not a primary constraint" (Adner & Levinthal, 2001).

Increasing performance at stable prices refers to the competitive strategy of firms to engage in product innovation in demand environments characterized by the emergence of technologically satisfied consumers even after consumers' functional requirements have been met; and to do so at stable product prices. The contrary view holds that in firms switch to process innovation (after consumers' functional requirements have been met) in order to increase profit margins.

3.3 Operationalizations of the Concepts

In order to test the basic claims of the theory archival data is used (see section 4.1.2 Data Sources). Consequently, it is important to define the relationships between the key concepts of the theory and data. There are 13 key constructs of the theory that must be operationalized and measured in order the test the seven basic claims (see Table 3). These are: (1) Performance, (2) Overall Performance, (3) Functionality Threshold, (4) Net Utility Threshold, (5) Functional Benefit (6) Luxurious Bargain, (7) Technologically

Satisfied Consumers, (8) Product Maturity, (9) Product Innovation, (10) Price, (11) Stable Price, (12) Mature Product Innovation, and (13) Performance Increase at Stable Prices.

THEORETICAL CONCEPTS	EMPIRICAL CONCEPTS	EMPIRICAL DATA
Performance	Product functionality in terms of processing speed necessary to render and display computer generated graphics (i.e. primary task requirement)	Indicators of performance are the Core & Memory Clock (in MHz), and Memory Bandwidth (in GB/s)
Overall Performance	Product functionality in terms of aggregate processing speed necessary to render and display computer generated graphics (i.e. primary task requirement)	Natural logarithm of the (mathematical) product of Core Clock, Memory Clock and Memory Bandwidth factors
Functionality Threshold	Minimum performance requirement product must meet to be considered for purchase by consumer	Consumer self-report in form of textual archival deposit on graphics cards review forums (product feedback); Performance
Net Utility Threshold	Greatest price consumer is willing to pay for product that meets her expectations	Consumer self-report in form of textual archival deposit on graphics cards reviews forums (product feedback); Performance; Overall Performance Indicator; MSRP. The net utility threshold involves an interaction between performance indicators and MSRP
Functional Benefit	Consumer perception about product performance in excess of customer expectations	Consumer self-report in form of textual archival deposit on graphics cards review forums (product feedback)
Luxurious Bargain	Consumer perception about a product that features seemingly unlimited performance surplus at a price she is willing to pay	Consumer self-report in form of textual archival deposit on graphics cards review forums (product feedback)
Technologically Satisfied Consumers	Consumer expressed satisfaction with the functionality and performance of a product	Consumer self-report in form of textual archival deposit on graphics cards review forums (product feedback)
Product Maturity	Product are considered mature if later editions are associated with stable or decreasing prices	AGP and PCIe based add-in-board Release Dates; MSRP.
Product Innovation	Products are considered innovative if later editions are associated with performance increases	AGP and PCIe based add-in-board Release Dates; Performance, Overall Performance
Price	Manufacturer's suggested retail price for a product (MSRP)	MSRP is associated with the majority of products in the GPUReview.com hosted database on graphics cards (see 4.1.2 Data Sources)
Stable Price	Reasonably narrow price selected from the absolute price range of all products	Narrow MSRP interval centered around the modal MSRP to represent the greatest number of products whose price variation is small
Mature Product Innovation	a) Product are considered mature if later editions are associated with stable/decreasing prices b) Product are considered innovative if later editions are associated with performance increases Mature product innovation occurs when both a) and b)	a) AGP and PCIe based add-in-board Release Dates; MSRP. b) AGP and PCIe based add-in-board Release Dates; Core Performance, Overall Performance If later releases tend towards price decreases AND performance increases, mature product innovation applies

Performance Increase at Stable Prices	a) Performance indicators increase over time b) Reasonably narrow price selected from the absolute price range of all products under review Performance Increase at Stable Prices occurs when a) and b) are true	a) AGP and PCIe based add-in-board Release Dates; Performance, Overall Performance b) Narrow MSRP interval centered around the modal MSRP to represent the greatest number of products whose price variation is small If later releases tend towards performance increase within a narrow price range, performance increase at stable prices occur

Table 3: Demand heterogeneity theory's relationships between theoretical concepts, empirical concepts and empirical data

(1) *Performance* is operationalized by three basic measures: the Core Clock (in MHz), Memory Clock (in MHz), and Memory Bandwidth (in GB/s). Paying attention to the first two measures is reasonable as manufacturers often feature these statistics in their AIB's marketing efforts. Memory Bandwidth is also featured in detailed product descriptions often found on manufacturers' websites.

(2) Another more comprehensive indicator of performance is *Overall Performance* which is derived from the Core Clock, Memory Clock and Memory Bandwidth performance indicators. The discussion of this measure is also located in the research findings section. It factors in the three advertised performance measures and scales it using the natural logarithm to decrease its range but retain the differences in intervals. Overall Performance is a derived measure attempting to better estimate the real performance consumers derive from AIB products (as opposed to theoretical performance in (1)). For example, a video card with a higher advertised core clock should theoretically perform better than a card with a lower core clock. That is not necessarily always the case. The overall performance of a card is determined by many factors: core clock, memory clock, memory bandwidth, driver support and efficiency, heat dissipation levels and so on. In the absence of controlled performance tests under real conditions for every card considered in this thesis, the next best solution is to derive an overall performance indicator that includes several advertised performance indicators actually available from the data. This new construct is still theoretical, but it is argued that it offers a closer estimate of real performance compared to any single indicator such as core clock alone. It is argued that a better estimate of real performance is defined by the interaction of advertised, discrete performance measures. In statistical procedures, interaction is usually captured through mathematical multiplication of contributing, quantifiable factors. This approach is used

here for its simplicity. Another approach would be to weight and add each contributing factor to derive overall performance. However, the basis on which to determine the weighting is not readily obvious. The question of how much more does the core clock, compared to the memory clock for example, contribute to overall performance is debatable and beyond the scope of this research. Equal weighting, defining the interaction term through multiplication, and scaling to a manageable level while preserving interval differences between measures using the natural logarithm is thus deemed an acceptable compromise.

(3) *Functionality threshold* is operationalized in two distinct but related ways: (1) qualitatively, consumers approve of, or affirm through self-report that a product meets or exceeds their minimum performance requirements. Instances of approval or affirmation are coded, classified and counted accordingly for each of the two graphics cards architectures (AGP & PCIe). This approach allows for direct evaluation of the claim that products meet consumers' functionality thresholds (C3); (2) quantitatively, AGP & PCIe based graphics cards are compared in terms of likelihood of meeting consumer performance thresholds. Mean performance for both architectures is measured and compared. If the difference in means is statistically significant, the architecture with higher average performance is more likely to meet consumers' performance thresholds. This approach helps ascertain one reason for consumer support for either legacy APG or novel PCIe architecture.

(4) *Net utility threshold* is operationalized in two distinct but related ways: (1) qualitatively, consumers approve of, or affirm through self-report that a product meets or exceeds their minimum performance requirements at a price they are willing to pay. Alternatively, consumers approve of, or affirm through self-report of the price for a product that meets or exceeds their minimum performance requirements. Instances of approval or affirmation are coded, classified and counted accordingly for each of the two graphics cards architectures (AGP & PCIe). The consideration of this construct must include the interaction of price and performance in consumers' self-report (i.e. price and performance are mentioned in conjunction). This approach allows for direct evaluation of the claim that products meet consumers' net utility thresholds (C4); (2) quantitatively, AGP & PCIe based graphics cards are

compared in terms of likelihood of meeting consumer net utility thresholds. Mean performance and mean price for both architectures are measured and compared. The customer preference decision matrix in Table 4 outlines all possible outcomes in terms of customer preference for AGP vs. PCIe architecture based on price-performance interaction.

		AGP Price			**PCIe Price**		
		*equivalent**	*lower**	*higher**	*equivalent*	*lower*	*higher*
AGP Performance	*equivalent*	n/a			equal preference	PCIe preferred	AGP preferred
	lower				PCIe preferred	PCIe preferred	undecided
	higher				AGP preferred	undecided	AGP preferred
PCIe Performance	*equivalent*	equal preference	AGP preferred	PCIe preferred	n/a		
	lower	AGP preferred	AGP preferred	undecided			
	higher	PCIe preferred	undecided	PCIe preferred			

Table 4: Customer preference decision matrix for AGP vs. PCIe architecture (all possible outcomes) based on the likelihood of meeting customer net utility thresholds; (*statistical difference or equivalence compared to the other bus architecture)

In reality, determining customer preference likelihood for AGP vs. PCIe architecture is much simpler than the matrix above would suggest: Given the same price, customers are more likely to prefer the architecture with higher mean performance. This applies for the special case of "stable prices" in particular (i.e. H4.3: AGP and PCIe are equally likely to meet customers' net utility thresholds at stable prices). On the other hand, given the same performance, customers are more likely to prefer the architecture with the lower mean price. This approach helps ascertain another reason for consumer support for either legacy APG or novel PCIe architecture.

(5) *Functional benefit*, (6) *luxurious bargain*, and (7) *technologically satisfied consumer* constructs are operationalized qualitatively: consumers approve of, or affirm through self-report that products (1) offer performance in excess of consumer functionality threshold; (2) offer seemingly unlimited performance at a very attractive price; and (3) allow consumers to meet technological needs. Instances of approval or affirmation are coded, classified and counted accordingly for each of the two graphics cards architectures (AGP & PCIe). Notice that these three constructs are closely related but differ somewhat in degree: products may lead to satisfied consumers only, may offer further functionality/performance, or may offer seemingly unlimited benefits, which the consumer does not hope to exploit fully but is happy to possess given the price. This approach allows for direct evaluation of the claims that consumers are technologically satisfied (C5), support products that offer functional benefits (C6), and support luxurious bargains (C7).

(8) *Product Maturity* is operationalized as Release Date with respect to Price Stability or price decreases; products belong to mature markets if the price is stable or decreasing over time. Dominant views on technology cycles suggest that price stability is due to decreases in product innovation and switching to process innovation: firms modify production processes to decrease costs of mature product classes featuring stable performance and functionality. Product maturity in the demand heterogeneity theory is contingent on the assumption that products indeed feature performance increases, but they do so at stable prices; i.e. a novel graphics card exceeding the performance class of an older graphics card, where both cards belong to the same price segment. However, this assumption is not taken for granted; it is actually tested using the Product Innovation measure (3) explained above. In essence, Adner & Levinthal equate Product Maturity with "price maturity", because they believe that consumers are not willing to pay more for performance increase given that they are already satisfied with the performance

they derive from existing products. Consumers will, however, consider paying the same price for greater performance (Adner & Levinthal, 2001). It is in that sense that products are deemed mature: they are stable in price and satisfy or exceed consumers' performance requirements. Notice that the prevailing view of immature technological products involves consumers' functional and performance task requirements that are not yet fully met.

(9) *Product Innovation* is operationalized as Release Date with respect to increases in performance measures, such as Core Clock, Memory Clock and Memory Bandwidth (explicitly stated measures in manufacturers' product advertising); i.e. a card released more recently constitutes a product innovation with respect to an older card *if* it features performance increases. A novel card that features the same performance as a significantly older card cannot be deemed a product innovation; it would merely constitute a re-release. Perhaps it helps to imagine, for example, Intel re-releasing today a desktop computer processor chip featuring the same performance as the legacy Pentium II chip. No matter how qualitatively different (innovative) that chip may be, in the desktop computers segment the clear trend is toward performance increases (consistent with Moore's Law: bi-annual doubling of chip clock in MHz). That is, the chief purpose of product innovation in the desktop computers CPU and GPU industry is to increase performance and functionality.

(10) *Price* is operationalized as Manufacturers' Suggested Retail Price (MSRP). This is not the only possible indicator of price. For example, there exists also the street price; the actual price consumers pay for products from retailers. However, street prices vary significantly from one retailer to another and it is difficult to collect a comprehensive data set on street prices for all the graphics cards products considered in this research. Nevertheless, retailers do base their actual street prices on manufacturers' suggestion. As the MSRP was available for the majority of products in this research, it is deemed an appropriate measure of price.

(11) *Stable Price* is operationalized as a reasonably narrow price range that is held constant over time. The detailed discussion of this measure and the criteria of "reasonably narrow" can be found in the

research findings section. The stable price is relative to the actual distribution of collected price data (see Appendix II). It essentially captures a sufficiently narrow "price segment" so as to be considered stable, but within which the majority of graphics cards are represented (this segment is centered on the modal price for all cards).

(12) *Mature Product Innovation* occurs when both (8) Product Maturity and (9) Product innovation constructs apply to a graphics cards architecture. For example, if for later editions of AGP-based graphics cards performance tends to increase, while the price tends to decrease, then the architecture in question is considered both mature and innovative. This situation suggests the intriguing possibility that, in high-tech markets, firms derive greater competitive advantage by focusing on processes that allow them to control costs but continue to produce innovative products, than by focusing on process or product innovation alone. Dominant views on technology cycles treat process and product innovation as discreet and alternate (cyclical) phenomena, interrupted by the emergence of technological discontinuities. The concept of mature product innovation captures both process and product innovation as concurrent phenomena.

(13) *Performance Increase at Stable Prices* is closely related to (12) mature product innovation. It differs from the later in that it takes price segmentation into consideration. Firms often segment markets in terms of consumers and price points. Focusing only on average prices and performance indicators for an entire family (architecture) of graphics cards to deduce mature product innovation might be misleading under certain circumstances. For example, if the majority of cards feature lower cost (i.e. price is skewed towards the lower range) but a few cards feature significantly higher performance (i.e. performance is skewed towards the higher range on a sufficiently high order of magnitude), then mature product innovation might occur, statistically, but in reality not apply to the majority of products. The stable price construct captures a price segment representing the greatest number of graphics cards compared to other price segments. If, within that stable price segment, performance for later editions of graphics card architecture tends to increase, then one can deduce increasing performance at stable prices.

3.4 Hypotheses

The seven basic claims of demand heterogeneity theory are stated as testable hypothesis and categorized according to their place within the theoretical framework.

Claim 1: Firms continue to engage in product innovation in mature product classes.

The demand heterogeneity theory's competitive strategy claims posit that technology firms engage in "product performance leadership" strategies in mature product classes. The following formal logical statement of the claim can be useful for testing. P1: The demand heterogeneity theory would predict that when product classes are mature firms will continue to innovate so as to increase the functional performance. We can thus test for two conditions; (1) product maturity, and (2) increased performance of mature products. A condition that signals product maturity is a decrease in the price of the product over time. On the other had continued product innovation in a mature product is signaled by increasing performance of the mature product over time. We can now test the following hypotheses to examine the validity of Claim 1:

H1.1: Mature product classes (Release Date) are associated with price (MSRP) decreases.

> Empirically we should be able to observe decreasing prices (MSRP) for later releases (Release Date) of the same product class (AGP or PCIe based AIB).

H1.2.1: Product innovations (as observed by Release Date) are associated with (Core Clock) performance increases.

> Empirically we should be able to observe increasing performance (Core Clock speed) for later releases (Release Date) of the same product class (AGP or PCIe based AIB).

H1.2.2: Product innovations (as observed by Release Date) are associated with (Memory Clock) performance increases.

> Empirically we should be able to observe increasing performance (Memory Clock) for later releases (Release Date) of the same product class (AGP or PCIe based AIB).

H1.2.3 Product Innovations (as observed by Release Date) are associated with Overall Performance increases.

> Empirically we should be able to observe increasing Overall Performance for later releases (Release Date) of the same product class (AGP or PCIe based AIB).

As the demand heterogeneity theory makes claims about performance increases at stable prices, the next set of hypotheses serve mainly as analytic controls to examine the general expectation of performance increases demanding higher prices. The following formal logical statement contrary to the Claim 1 can be useful for testing. P1(c): The technology cycles theory would predict that product classes with higher performance demand higher prices due to firms engaging in product innovation (as opposed to process innovation in which case consumer task requirements have been satiated and the focus switches to cost control).

This proposition is included for three primary reasons: first, the claim of increasing performance at stable prices is a central claim of the demand heterogeneity theory and thus warrants deeper probing; second, searching for contrary evidence –the possibility of increasing performance at increasing prices-accords with the scientific research principle that active pursuit of evidence on the contrary strengthens the rigor and validity, introduces balance to, and flushes out boundaries of derived conclusions; and third, the data for testing the contrary proposition is readily available and its inclusions serves to preemptively address the reasonable expectation of higher prices for higher performance. We can now test the following hypotheses to serve as contrary evidence claims to the validity of Claim 1:

H1.3.1: Performance increases (as measured by Core Clock) are associated with price (MSRP) increases.

> Empirically we should be able to observe increasing performance (Core Clock) for more expensive products (MSRP) of the same product class (AGP or PCIe based AIB).

H1.3.2: Performance increases (as measured by Memory Clock) are associated with price (MSRP) increases.

> Empirically we should be able to observe increasing performance (Memory Clock) for more expensive products (MSRP) of the same product class (AGP or PCIe based AIB).

H1.3.3: Overall Performance increases are associated with price (MSRP) increases.

> Empirically we should be able to observe increasing performance (Overall Performance) for more expensive products (MSRP) of the same product class (AGP or PCIe based AIB).

Claim 2: Product innovations feature Overall Performance increases at Stable Prices.

This is another important claim of the theory; however, while Claim 1 deals with price-performance relationships over a wide price range, Claim 2 captures the price-performance relationship over a narrow price range. The following formal logical statement of the claim can be useful for testing. P2: The demand heterogeneity theory would predict that products within a narrow price range still tend to increase in performance over time. (Notice that if the more novel products feature performance increases, they are deemed product innovations.) We can now restate the Claim 2 as the following hypothesis:

H2: Product innovations (as observed by Release Date) feature Overall Performance increases at Stable Prices

> Empirically we should be able to observe increasing performance (Overall Performance) for later releases (Release Date) of the same product class (AGP or PCIe based AIB), where the products under consideration do not vary in price significantly from each other.

The next hypothesis also serves mainly as analytic control to examine the general expectation of performance increases demanding higher prices even when the products under consideration are similarly priced. The following formal logical statement contrary to Claim 2 can be useful for testing. P2(c): The technology cycles theory would predict that product classes with higher performance demand higher prices due to firms engaging in product innovation (as opposed to process innovation in which case consumer task requirements have been satiated and the focus switches to production cost control). This is true no matter how narrow the price range of products under consideration. We can now test the following hypothesis to serve as contrary evidence claim to the validity of Claim 2:

H2.1: Overall Performance is associated with price increases even within a narrower price range.

> Empirically we should be able to observe higher prices for better performing products of the same product class (AGP or PCIe based AIB), even though the products under consideration do not vary in price significantly from each other.

Claim 3: Consumers support products that meet their functionality thresholds.

Without the benefit of "real-life" tests, customers have to rely on advertised performance measures, such as Core Speed and Memory Speed to deduce the potential functional performance. Alternatively, customers can read product feedback evaluations located on merchant web-sites to see if the product under consideration is likely to meet their performance thresholds. If others who own the product already express approval for it, because it meets or exceeds their functional thresholds, then customers considering the purchase are likely to be swayed in its favor as well. Questions of expressed consumer support are examined qualitatively in this research. The following formal logical statement of the claim can be useful for testing. P3: The demand heterogeneity theory would predict that customers would express support for products that meet their functionality thresholds. We can now restate the Claim 3 as the following hypothesis:

H3: Consumers express approval for products that meet their functionality thresholds.

> Empirically we should be able to observe self-reported customer support for products which meet their functionality thresholds in form of text passages from product evaluations under the "pro" heading which refer to functional requirements being fulfilled.

It is difficult to determine exact functional thresholds for all customers as functional thresholds are heterogeneous (i.e. differ from customer to customer) and since that particular data is not available for this study. The hypothesis above dealt with support for products and assumed that customers are aware of their own task requirements and know when a product is meeting their particular functional requirements. It is possible, however, to test for the likelihood of product architectures (i.e. in the aggregate, AGP vs. PCIe) meeting functionality thresholds. For example, if Claim 3 is true for AGP cards despite the availability of newer PCIe cards then it is expected that the advertised functional performance of AGP is not significantly lower compared to PCIe. In other words, both AGP and PCIe are equally likely to meet customers' functionality thresholds. The following formal logical statement can be useful for testing. P3.1: If AGP and PCIe based graphics cards do not differ significantly in performance, then they are equally likely to meet customer's functionality thresholds. We can now test the following hypotheses to examine the validity of P3.1:

H3.1: AGP and PCIe advertised functional performance measures are equally likely to meet customers' functional thresholds.

> Empirically we should be able to observe no statistically significant difference in advertised functional performance measures (core clock, memory clock) between the two architectures (AGP vs. PCIe based AIB's).

Similarly, in the special case of stable prices the following logical statement applies: P3.2: If AGP and PCIe based graphics cards do not differ significantly in performance within a narrow price range, then they are equally likely to meet customers' functionality thresholds. We can now test the following hypotheses to examine the validity of P3.2:

H3.2: AGP and PCIe advertised functional performance measures are equally likely to meet customers' functional thresholds at stable prices

> Empirically we should be able to observe no statistically significant difference in advertised functional performance measures (core clock, memory clock) between the two architectures (AGP vs. PCIe based AIB's) where products under consideration are selected from a narrow price range.

Claim 4: Consumers support products that meet their net utility thresholds.

This claim is dealt with in a similar fashion to Claim 3. The only difference is that for C4, both the interaction between functional thresholds, and the maximum price customers are willing to pay for the product needs to be captured. As with Claim 3, questions of expressed consumer support are examined qualitatively. The following formal logical statement of the claim can be useful for testing. P4: The demand heterogeneity theory would predict that customers would express support for products that meet their functionality thresholds *at* a price they deem reasonable. We can now restate the Claim 4 as the following hypothesis:

H4: Consumers express approval for products that meet their net utility thresholds.

> Empirically we should be able to observe self-reported customer support for products which meet their net utility thresholds in form of text passages from product evaluations under the "pro" heading which refer to functional requirements being fulfilled at prices reviewers are willing to pay. That is, customers would refer to the products performance and price as being satisfactory.

Again, it is possible to test for the likelihood of product architectures (i.e. in the aggregate, AGP vs. PCIe) meeting net utility thresholds. The following formal logical statement can be useful for testing. P4.1: If AGP and PCIe based graphics cards do not differ significantly in performance *and* price then they are equally likely to meet customers' net utility thresholds. We can examine two conditions: (1) functional performance equivalence (i.e. H3.1) and (2) price equivalence to test the validity of P4.1:

H4.1: AGP and PCIe are equally likely to meet customers' net utility thresholds.

> We can deduce the validity of 4.1 if there is empirical evidence to support H3.1 *and* H4.2.

H4.2: AGP and PCIe do not differ significantly in average price.

> Empirically we should be able to observe no statistically significant difference in price (MSRP) between the two architectures (AGP vs. PCIe based AIB's).

That is, if the advertised functional performance as well as average price do not differ significantly between AGP and. PCIe, then both are equally likely to meet customers' net utility thresholds.

Similarly, in the special case of stable prices the following logical statement applies: P4.3: If AGP and PCIe based graphics cards do not differ significantly in performance within a narrow price range, then they are equally likely to meet customers' net utility thresholds. We can now test the following hypotheses to examine the validity of P4.3:

H4.3: AGP and PCIe are equally likely to meet customers' net utility thresholds at stable prices

> Empirically we should be able to observe no statistically significant difference in Overall Performance between the two architectures (AGP vs. PCIe based AIB's), where products under consideration are selected from a narrow price range.

In this case, the price is held fixed within a narrow price range (i.e. it is stable). Therefore, it is sufficient for one bus architecture category to offer greater Overall Performance to be considered more competitive in terms of net utility.

Consumer satisfaction claims are inherently subjective and qualitative. As the qualitative, self-reported product-satisfaction data is available, the following set of claims can also be examined:

***Claim 5**: Consumers (whose functional and utility thresholds are met) are technologically satisfied.*

The following formal logical statement of the claim can be useful for testing. P5: The demand heterogeneity theory would predict that when product classes meet consumers' functionality and/or net utility thresholds, then consumers are technologically satisfied. That is., consumers express that products meet their functionality and/or utility thresholds and are thus, by definition, considered technologically satisfied. In addition, consumers may explicitly state that they are technologically satisfied without specific reference to their functionality and/or utility thresholds being met or exceeded. We can now test the following hypothesis to examine the validity of Claim 5:

> H5: Consumers (whose functional and utility thresholds are met) express that they are technologically satisfied.
>
> > Empirically we should be able to observe self-reported customer satisfaction with either or both product architectures (AGP and PCIe based AIB's) in form of text passages from product evaluations under the "pro" heading which explicitly state satisfaction with the product.

Claim 6: Consumers support products that offer functional benefits.

The following formal logical statement of the claim can be useful for testing. P6: The demand heterogeneity theory would predict that consumers appreciate product performance and functionality that exceeds their immediate task requirements at a price they are quite willing to pay; i.e. consumers enjoy functional benefits. We can now test the following hypothesis to examine the validity of Claim 6:

H6: Consumers express approval for products that offer functional benefits

> Empirically we should be able to observe self-reported customer support for products of either or both product architectures (AGP and PCIe based AIB's) that exceed their immediate task requirements at a price they are willing to pay in form of text passages from product evaluations under the "pro" heading which refer to functional performance in excess of consumers' immediate needs.

Claim 7: Consumers support luxurious bargains

The following formal logical statement of the claim can be useful for testing. P7: The demand heterogeneity theory would predict that in the high-tech graphics cards sector, products are considered luxurious bargains if they exceed consumers' task requirements by a wide margin at a price they are willing to pay. Moreover, consumers may express that they feel that products offer seemingly unlimited functionality and performance (i.e. "luxurious performance"). We can now test the following hypothesis to examine the validity of Claim 7:

H7: Consumers express approval for luxurious bargains

> Empirically we should be able to observe self-reported customer support for products of either or both product architectures (AGP and PCIe based AIB's) that in their opinion offer unlimited functionality and performance at a price they are willing to pay in form of text passages from product evaluations under the "pro" heading which explicitly refer to seemingly unlimited benefits beyond immediate consumer requirements.

4 Research Methods and Data Sources

A mixed method strategy has been chosen for this study as it involves both quantitative and qualitative methods in a complementary manner. The mixed method is necessary due to the archival nature of the data available, which include quantitative and qualitative indicators needed for testing the chief claims of the demand heterogeneity theory. For example, indicators of AIB's price/performance interaction claims are quantifiable and thus amenable to quantitative analysis. Indicators pertaining to customer product evaluation and self-reported support for product categories call for qualitative text analysis, since the data has already been deposited in the form of open-ended comments.

The main advantage of the mixed method consists of strengthening construct validity through methodological and data triangulation (Mingers & Brocklesby, 1997; Brannen, 2005). For example, in the case of heterogeneous threshold claims -consumers support products that meet their functionality/net utility thresholds (see 3.4 Hypotheses)- the greater likelihood of some products meeting heterogeneous thresholds over others can be ascertained quantitatively using statistical procedures (ex: difference of means). Those claims can also be ascertained qualitatively by asking consumers directly through questionnaires or conducting content analysis on texts containing evidence for such claims.

The two methodological approaches in this research (discussed in more detail in section 4.3 Data Analysis) are: (1) qualitative content analysis (using coding, categorizing and counting) and (2) statistical hypothesis testing for association (using partial correlation coefficient statistic) and difference of means (using the independent samples t-test statistic) between constructs.

4.1 Data Collection

4.1.1 Background on the Industry Sector

There are several reasons why the enthusiast graphics cards industry was chosen in order to test the theory of demand heterogeneity: First, the computer peripherals industry is a global, multibillion dollar industry. A better understanding of demand drivers, then, is important for firms to take advantage of business opportunities that this particular market offers. Jon Peddie Research, a leading research and consulting firm on computer graphics and multimedia, indicated in its Q2'06 report that the performance and enthusiast worldwide shipments amounted to US$4.3 billion, or 73% out of a total US$5.9 billion desktop GPU market (Business Wire, 2006). Second, Adner & Levinthal illustrate a central point of their theory –continued performance increases at relatively stable prices- noting that this has been markedly observed in electronic-based technologies, but not handled in the literature yet. They refer to personal computers, VCRs, fax machines, copiers and other consumer electronics, all of which have witnessed objective performance increases yet remained stable in price over a number of years (Adner & Levinthal, 2001). The graphics cards industry is therefore very suited for testing Adner and Levinthal's theory as it belongs to a subset of industries producing electronics-based technologies, and personal computers technologies in particular. Third, this industry is contingent upon the motherboard industry in the sense that the developments of motherboard data bus technologies (protocols and form-factors/topologies) that interface with the graphics cards greatly influence the development of graphics cards themselves. Graphics cards manufacturers must operate within the constraint of data buss interfaces which have significantly changed in the recent past as discussed below. With respect to the graphics cards industry such transitions are considered radical architectural innovations which pose interesting questions of longevity of AIB's based on the older interface and the emergence of new dominant AIB's based on the novel interface. As such transitions are central to this research, further elaboration is warranted.

The PC peripherals industry witnessed the advent of the Peripheral Component Interconnect Express (PCIe) data bus interface, which is incompatible and mutually exclusive with the older Accelerated

Graphics Port (AGP) interface. Manufacturers of graphics processing chips (GPU's) and graphics card add-in-boards (AIB's) are faced with a dilemma: should they continue producing and supporting AGP based cards or should they abandon AGP and focus entirely on PCIe? Consumers are faced with a similar dilemma: should they stick to the older trusted AGP interface or switch to the newer PCIe interface when they decide to upgrade the AIB's. The Accelerated Graphics Port (AGP), first introduced in 1996, was intended to overcome the limitations of the Peripheral Component Interconnect (PCI) data bus, which was developed in 1992. AGP and PCI designs differ in data bandwidth and form factor. An AGP card does not fit into the PCI slot and vice versa. Since its introduction, most graphics cards manufacturers have focused on AGP cards in their "enthusiast" product lines.

Since then, the PC industry was introduced to the PCI Express (PCIe) interface, approved as a standard on April 17, 2002 (M.D., 2003). PCIe is backward software compatible with the familiar PCI data bus with which it can coexist and offer up to twice the speed of the AGP interface (Bhatt, n/a). For that reason it is considered an incremental evolution of the PCI bus architecture. However, as Dewar and Dutton argue, the newness or radicalness of a technological innovation is relative to the unit of adoption (Robert D. Dewar, 1986). Given the incompatibility of AGP and PCI, from the perspective of AIB chipset and board manufacturers, PCIe can be viewed as a radical architectural innovation.

In June 2004, Microsoft, answering to consumer and industry concerns, indicated that it will support PCIe with its software, and that PCIe is destined to replace AGP in the graphics market and projected that the first motherboards with PCIe interfaces will be available in the summer of that same year, but that that depended on the motherboard manufacturers (Microsoft Corporation, 2004). The first PCIe graphics cards started appearing at the end of the second quarter in 2004 (Shilov, 2005). Industry observers and graphics cards consumers have predicted the disappearance of AGP based AIB's for quite some time. More than three years have passed since the summer of 2004 and AGP cards with cutting edge chipsets are still being released; the sudden death of AGP that was so widely predicted has not materialized.

4.1.2 Data Sources

Two primary sources of data for this study have been indentified: (1) a database containing quantitative data points, such as price, performance measures and release dates on graphics cards, and (2) a qualitative source of textual data on user feedback on graphics cards.

1. GPUreview.com hosts an extensive video card database showing over 500 graphics cards models. It orders graphics cards by card name (including the AGP/PCIe designation), chip name (generation), manufacturer, core and memory clock, and memory bandwidth. The last three categories allow for ordering by theoretical performance and measurement of the rate of performance increase over time. Most importantly, GPUReview provides the release date for each item in the database so as to allow longitudinal considerations. This data set will be analyzed quantitatively.

2. The newegg.com e-commerce merchant has an enormous customer base. Their enthusiast graphics card buyers seem particularly keen on posting feedback. This data will be analyzed qualitatively. Newegg.com offers detailed specifications on sold products (model, interface, chipset, memory type and size, and general features) and detailed related customer reviews. The latter include quantitative data points on the purchase date, self reported 'tech level' (Likert scale), duration of ownership and a five-point subjective review score (very poor to excellent). However, the focus will be on individual feedback entries to specific products. Evaluations of purchased products and feedback posted on this merchant web-site are particularly valuable for this research as these are going to provide a primary source of qualitative data to test the hypothesis pertaining to customer product support and the reasons thereof.

The data used in this study was gathered from archival sources due to its availability as well as inherent advantages. An advantage of archival data is that such data provides unobtrusive measures to scrutinize 'real' processes, and therefore avoids reactivity between the researcher and research participant (Davis, 1990). Nevertheless, Palys cautions that even archival data is deposited with an audience in mind, meaning that reactivity issues can never be completely removed. Therefore, as researchers "we should still be careful about how much confidence we place in the conclusions" (Palys, 2003).

The inclusion of self-reported user product evaluations, feedback, and support for products located on merchant web-sites offers another advantage: It addresses what Rogers terms the "respondent recall problem" with respect to adopter surveys: when asking about factors that contribute to the diffusion of an innovation in adopter surveys, respondents often cannot recall their exact reasons for the adoption, or they provide post-facto reasons (Rogers, 1983). Of course, this has negative implications for drawing conclusions about causality because the temporality criterion is violated; respondents cite factors that purportedly influenced their adoption of an innovation *after* the adoption has occurred. As a remedy, Rogers suggests "point-of-adoption" studies: "respondents provide details about the adoption of an innovation at the time that they adopt" (Rogers, 1983). The type of information contained in user feedback on purchased products (time of purchase and length of ownership) allows for control of the respondent recall problem and produces more confidence in causal claims regarding reasons for user adoption of technology. Before the raw data could be used, however, it had to be prepared for the actual analysis. This process is outlined in the next section.

4.2 Data Preparation

The preparation of data is a crucial step in order to enable data analysis and render it meaningful. However, there exists a danger of introducing systematic bias through overzealous "data-massaging" and thus influencing the outcomes of findings (Palys, 2003). Therefore, all data preparation efforts have to be justified and transparent in order to enhance the validity and replication of the study. The two major data sets used in this study are: (1) the SPSS "gpuReviewFiltered.sav" database, and (2) the "Useful Review Sample" data set. Their preparation is discussed next:

1. The GPUReview data is imported into a SPSS database (gpuReviewFiltered.sav) and filtered so as to exclude workstation and mobile graphics cards (FireGL, FireMV, Quadro, Mobility and Go lines), which are not of interest in this study. Mobile graphics cards cannot be (easily) swapped by users themselves. Therefore they do not feature prominently in the after-market upgrade activity. Workstation graphics cards are either cheap and offer basic functionality (ex: desktop acceleration) and are of no interest to enthusiast users, or they are extraordinarily expensive and are targeted towards professional photo/video/graphics content developers. Non-ATI and Nvidia chip based cards were also excluded as most of these are not targeted towards the enthusiast segment. Many of the alternative GPU manufacturers were out of business at the time of this writing (September 2008). This leaves the more recent enthusiast segment covering the transition from AGP to PCIe. Another reason for selecting the enthusiast graphics cards user segment as the target population for this study is that it appears to be disproportionately represented in forums and web merchant-hosted product evaluations. This makes it very suitable for the study of demand context dynamics postulated by Adner and Levinthal's demand heterogeneity theory. Overall, the GPUReview.com dataset includes 132 (59%) AGP and 92 (41%) PCIe cards for a total of 224 cards (Table 5).

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	AGP	132	58.9	58.9	58.9
	PCIe	92	41.1	41.1	100.0
	Total	224	100.0	100.0	

Table 5: Descriptive Statistics for "gpuReviewFiltered.sav" SPSS Dataset, breakdown by Bus Architecture (GPUReview, 2008)

2. The newegg.com "Useful Reviews Sample" consists of 30 customer product reviews of desktop graphics AIB's, divided in two equal parts by bus architecture. The sampling was conducted as follows: All product reviews in the desktop graphics card category were first searched for items containing the "AGP" and then "PCI Express" keywords. The queries were sorted by "helpfulness": registered users of the newegg.com website reading specific product reviews have the option to answer a question regarding the usefulness of the review they have just read. A prompt reads: "X out of Y people found this review

helpful. Did you?" Three responses are possible: a) not to respond to the prompt (missing data), b) "yes", c) "no". Out of all reviews in this sample universe, those with the greatest number of positive answers to this prompt have been selected for closer inspection. Top 15 reviews in terms of the total number of respondents who found this particular product review "helpful" were selected for each category. This sample illustrates the kind of language, concepts and information contained in reviews that the majority of readers find meaningful. It is assumed that respondents mark a product review as meaningful if it positively helped them with a purchase decision or answered questions they deemed important. This selection of "useful reviews" is considered representative of reviews that could reasonably have a significant impact on the reader. Choosing a random sample was neither feasible nor practical given over 20,000 reviews. There was no practical way to navigate to, for example, review #7893 quickly, which could have been selected by a random number generator. Accurately defining the sample frame was also difficult as new reviews are constantly being added. As already mentioned, the SPSS data set will be subjected to statistical analysis, while the newegg.com data set will be subjected to content analysis. The specifics of these different methods are discussed below.

4.3 Data Analysis

4.3.1 Statistical Analysis Methods

The two statistical procedures used in this research are: (1) partial correlation and (2) independent samples t-test. Both are discussed in terms of their function and application in this research:

1. Hypothesis stating associations between quantifiable variables (release date, price, and performance indicators) will be tested using the partial correlation procedure. Statistical correlation is commonly used to assess the direction and strength of linear, bivariate relationships (Miller & Whitehead, 1996) such as those expressed as *competitive strategy claims* (see section 3.4 Hypotheses) of the demand heterogeneity theory. Competitive strategy claims involve three bivariate relationships: (1) 'release date–performance' (product innovation); (2) 'release date–price' (product maturity); and (3) 'price-

performance'. Linearity is assumed for three reasons: (1) the theory does not postulate any particular type (linear, quadratic, exponential…) of bivariate association, so that asserting any such type would be arbitrary; (2) linear association is the simplest type of association; and (3) linear association is sufficient to show the presence, direction, and strength of a bivariate relationship (and that is sufficient for ascertaining competitive strategy claims in this particular research).

Moreover, partial correlation allows for controlling the effects of a third variable which may introduce spuriousness into the observed relationship (Miller & Whitehead, 1996). In other words, an observed relationship between two variables may be due to the effect of a third variable which "acts in the background". The relationships mentioned above will be controlled for the effects of data bus architecture (AGP/PCIe), thus any observed relationships can be ascribed to the two variables in question with more confidence without second-guessing oneself whether the data bus had anything to do with the observation.

2. The independent samples t-test procedure will help in testing *heterogeneous thresholds claims* (see section 3.4 Hypotheses). It will mainly serve to compare and contrast the two categories (AGP/PCIe) with respect to numeric measures and determine how both categories compare in terms of meeting consumer thresholds. The t-test is one of the most common parametric tests used for scale or interval variables for which a mean can be calculated (Miller & Whitehead, 1996). Therefore, it will be used to analyze differences in mean (1) performance measures (core clock, memory clock, memory bandwidth, and overall performance), (2) price, and (3) release dates (novelty) between AGP and PCIe graphics cards. Another useable parametric test would be the z-test; however, the t-test is preferred as it is more robust with respect to sample size and normal distribution assumptions (Miller & Whitehead, 1996). The sample sizes involved in this research are for the most part adequate (i.e. $N>>30$ for AGP or PCIe AIB's), however, the "stable price" sub-sample consists of less than 45 cards in total (i.e. $N<30$ for AGP or PCIe AIB's). This particular sub-sample necessitates the t-test over the z-test.

Finally, it should be noted that the two categories are indeed independent from each other (sample independence assumption) as each is derived from a different population of graphics cards. In other words, it is not the case that a single population (ex: AGP cards) has received a treatment (ex: an interface upgrade to become PCIe cards) and is measured before and after the treatment, in which case one would regard them as paired, or matched samples; each card is manufactured as either an AGP or PCIe based AIB. Besides the statistical methods described in this section, the mixed method strategy in this study also involves qualitative methods described in the next section.

4.3.2 Qualitative Content Analysis

Claims dealing with expressions of support or disapproval for a graphics card, such as *heterogeneous threshold claims* and *technologically satisfied consumers claims*, are analyzed in a qualitative fashion using content analysis. (Notice that heterogeneous thresholds claims are examined using quantitative methods as well thus taking advantage of the method triangulation principle inherent in the mixed method approach).

The basic tenets of content analysis involve coding scheme development, concept frequencies counting and categorization (Krippendorff, 2004). The coding scheme itself can emerge from the text in a grounded theory manner, meaning that the researcher approaches the text without theoretical preconceptions. That is, theoretical concepts are grounded in the text (in this case) as opposed to being imposed by the theory. In essence, as the researcher engages the text, certain themes begin to emerge that can be classified and grouped, and implications are drawn about the characteristics of dominant themes and their relationships to each other, to the text, or to the audience (Glaser & Strauss, 1967). This is the so-called emergent approach or grounded theory approach to content analysis.

However, this research relies on the hypothetico-deductive logic in which the theory is imposed "from above". Therefore, the coding scheme is also influenced by the theoretical framework used in the study (Palys, 2003); the design heterogeneity theory. But although the majority of codes used in this coding framework are derived from the theory of demand heterogeneity, some also derive from the network externalities conceptual framework. The reasons for the inclusion of the latter is due to the recognition that upon the initial reading of users' product evaluations feedback, possible codes which are clearly associated with network externalities were readily apparent from the text. Other relevant codes that emerged from the text in the grounded theory manner (i.e. codes that were not imposed by a pre-formulated theory, as explained above) were also admitted in this study. This is the case because any single theory imposed on the text is likely to miss some emergent concepts which can often be very instructive, or even fatal to the theory.

Consumers' feedback on graphics cards allows for 'pro' and 'cons' comments to be coded, counted and categorized by consumer's self-reported reasons for product support or lack thereof. For example, a user might disapprove of a product for reasons related to cooling fan noise levels, overheating, stability issues, bad hardware drivers, performance levels, excessive current draw necessitating stronger power supplies and so on. In other words, the qualitative justification for product support (or criticism) provides an avenue for determining the effects of network externalities, for example, on consumer support. If a user states: "I purchased a PCIe card, because everyone is switching to PCIe anyways", this would be coded as support for a PCIe card due to "perceived installed base" reasons.

The three coding scheme groups used for content analysis are thus: (1) demand heterogeneity codes; (2) network externalities codes; and (3) emergent codes. The following list outlines when and how given passages in the text were coded:

Demand Heterogeneity codes include passages pertaining to:

- Technologically satisfied: comments about being happy with product performance
- Enjoys functional benefits: functionality derived in excess of functional requirements (ex: product can be over-clocked successfully)
- Utility threshold: comments regarding functionality in conjunction with price paid
- Functionality threshold: comments regarding whether functional requirements are met (ex: product serves my purposes)
- Luxurious bargain: coded for references to product's seemingly unlimited exogenous functional performance in the subjective assessment of reviewers, while acknowledging that the price was "right"
- Price stability or decrease while meeting or exceeding reviewers' functional requirement: coded when product met functional requirements but was purchased at a lower price than was anticipated (or when waited to purchase such product after price decreased)

Network Externalities codes include passages pertaining to:

- Cooling solution to the products under review
- Hardware and software installation process
- Interaction within reviewers' existing PC environment (hardware/software)
- Form-factor
- Generated heat levels (since, if unacceptable, might imply additional costs for after-market coolers)
- Generated noise levels (since, if unacceptable, might also imply additional costs for after-market coolers that are quieter)
- Performance stability (since, if unacceptable, might imply additional costs for an alternative hardware/software environment)

- Power supply requirements (since the product under review might require a higher wattage power supply, thus implying additional costs)
- Software drivers needed for proper and efficient operation
- Compatibility with reviewers' existing hardware/software
- Manufacturers' customer (rebates, returns, exchanges) and technical support
- Aesthetics (physical, picture quality)
- Switching costs: coded for references stating that additional costs are required, which impede the purchase
- Installed base: coded for references made to a group of other user of the same product family

The following codes emerged from the text:

- Projected future utility: coded if references made to further functional benefits in the future with respect to the product
- AIB serving as a network externality with respect to reviewers' PC environment: coded if references made that the product itself prolonged the life-cycle of a PC system, or enhanced the functionality of the existing system.
- Price: coded when mentioned without relating it to product functionality or performance.
- Disapproval of other reviewers

Upon mapping the text to codes outlined above, further classifying and counting of frequencies allows for determining the relative strength of the various theoretical concepts in terms of how prominent these feature in users' feedback comments. For example, if many users claim that they are very happy with their purchased products, then it can be concluded that there exists some support for the technologically satisfied consumer claim suggested by the demand heterogeneity theory. Having outlined the qualitative and quantitative methods used in this research, actual data can be engaged in earnest in the next section.

5 Research Findings

5.1 Quantitative Analysis

The initial step in this research involves the characterization of AIB graphics cards evolution in terms of AGP to PCIe architecture transition. This step provides a general overview of the AIB graphics cards data under consideration. It also serves to examine the first claim.

Claim 1: Firms continue to engage in product innovation in mature product classes

At the time of this writing (September, 2008) AGP graphics cards are still available for sale. The newegg.com site offers 40 different AGP models, ranging from $25 – $200 USD (newegg.com, 2008) while the Canadian web-retailer tigerdirect.ca website offers 47 models (tigerdirect.ca, 2008). Needles to say, both websites still offer the ancient PCI (developed 16 years ago in 1992 and not to be confused with more recent PCI Express data bus) based graphics cards, with 45 and 28 different models respectively. The top of the line Radeon HD 3850 AGP model features a 2560X1600 resolution, HDTV 1080p capability, 720MHz core clock, 512MB @ 1820MHz GDDR3 memory, 256-bit memory interface, and a staggering 320 stream processors with a price tag of $298.99 CAD (tigerdirect.ca, 2008).

While this example serves as an illustration, more rigorous evidence for continued production of AGP based AIB is provided by the GPUReview data set. Figure 3 reveals the approximate transition from the AGP to PCIe architecture. The release of PCIe based cards starts after Q2/2004 and picks up in frequency from then on. Around the same time, the frequency of AGP based cards starts to level off, with the last data point in the GPUReview data set being represented in Q2/2008.

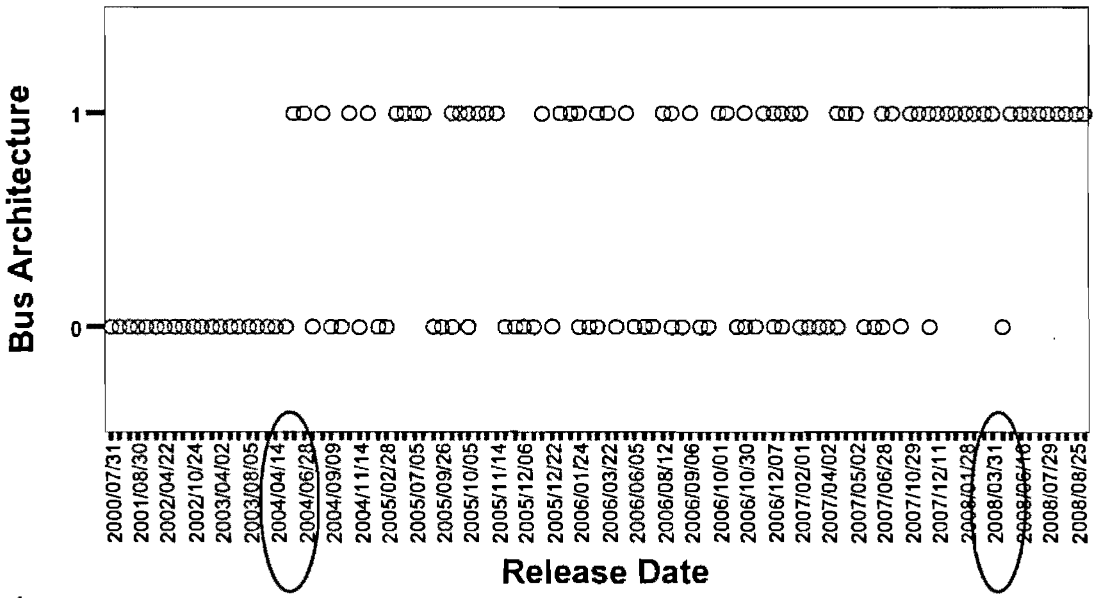

Figure 3: The Transition from AGP (0) to PCIe (1) Architecture, 2000-2008, gpuReviewFiltered.sav (GPUReview, 2008)

The time period between Q2/2004 and Q2/2008 therefore represents a transition period of about four years from AGP to PCIe, which, in terms of consumer electronics and especially computer components, represents an extraordinarily long amount of time given the fast pace of technological change in these industries. Therefore, manufacturers have been releasing novel AGP cards for at least four years after the introduction of the new PCIe standard. ATI and Nvidia have yet to announce that they will stop producing GPU's for the AGP data bus. In other words, there is some evidence to accept Claim 1. However, hypotheses necessary to strengthen the first claim further involve associations between price, release date and performance variables (a short overview of respective distributions is located in Appendix II):

H1.1: Mature product classes (Release Date) are associated with price (MSRP) decreases

A MSRP over Release Date scatter plot does not reveal any apparent association between the two for the PCIe buss; the price over time appears randomly distributed (Figure 4). The partial correlation, controlling for the bus architecture, however, confirms a slight negative (coefficient = -.16) association between MSRP and Release Date at the .05 significance level (one-tailed, since the hypothesis implies a direction for the relationship) (Table 6). Therefore, H1.1 is supported; product classes are in fact mature as indicated by falling prices overall.

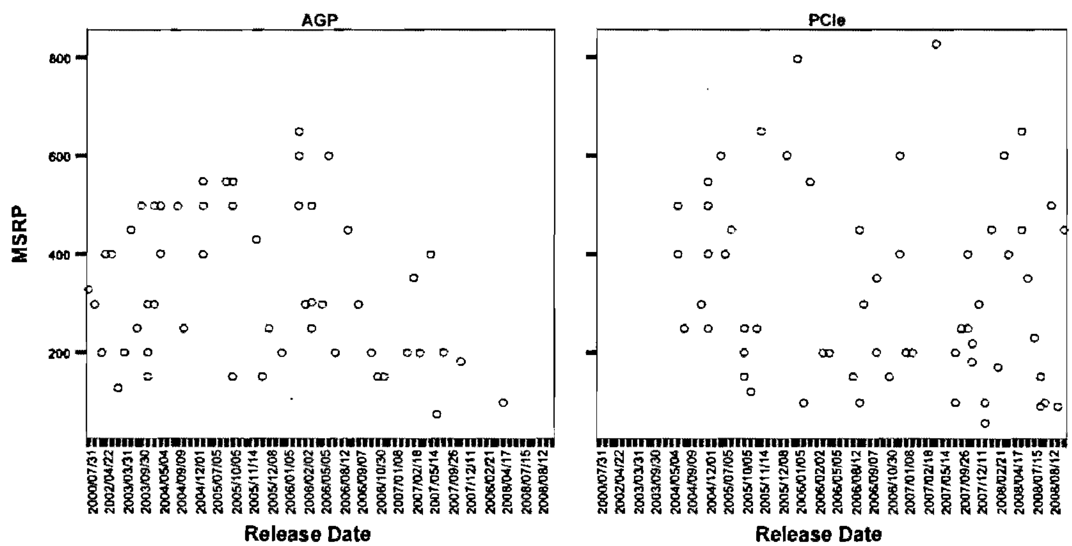

Figure 4: Scaterplot of MSRP (in USD) over Release Date, AGP vs. PCIe, gpuReviewFiltered.sav (GPUReview, 2008)

Control Variables			MSRP	Release Date
Bus Architecture	MSRP	Correlation	1.000	-.156
		Significance (1-tailed)	.	.047
		df	0	115
	Release Date	Correlation	-.156	1.000
		Significance (1-tailed)	.047	.
		df	115	0

Table 6: Partial Correlation between MSRP and Release Date controlling for Bus Architecture

H1.2.1: Product innovations (Release Date) are associated with (Core Clock) performance increases

In terms of performance, most common indicators of performance such as the GPU (core) and memory clock-speed are examined. As was expected, Core Clock speeds have been increasing with the Release Date (Figure 5). The positive correlation between product innovation and performance is strong (coefficient = .73) and significant at the .001 level (Table 7). Therefore, H1.2.1 is supported.

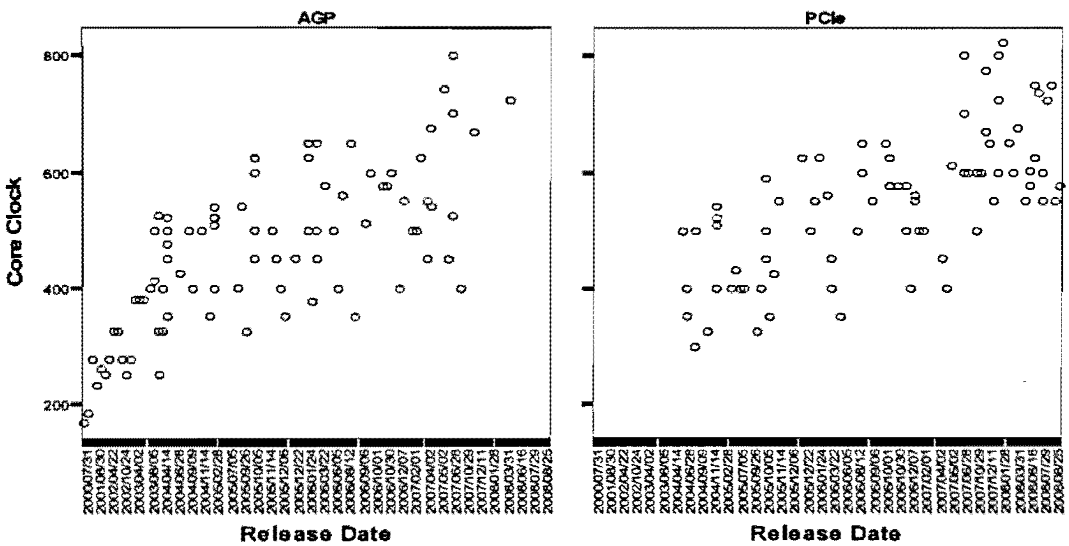

Figure 5: Scatterplot of Core Clock (in MHz) over Release Date, AGP vs. PCIe, gpuReviewFiltered.sav (GPUReview, 2008)

Control Variables			Release Date	Core Clock
Bus Architecture	Release Date	Correlation	1.000	.731
		Significance (1-tailed)	.	.000
		df	0	168
	Core Clock	Correlation	.731	1.000
		Significance (1-tailed)	.000	.
		df	168	0

Table 7: Partial Correlation between Core Clock and Release Date controlling for Bus Architecture

H1.2.2: Product innovations (Release Date) are associated with (Memory Clock) performance increases

From the scatter-plot in Figure 6 it appears that Memory Clock-speeds are positively associated with Release Date as well. The positive correlation between product innovation and performance is also rather strong (coefficient = .61) and significant at the .001 level (Table 8). Therefore H1.2.2 is supported.

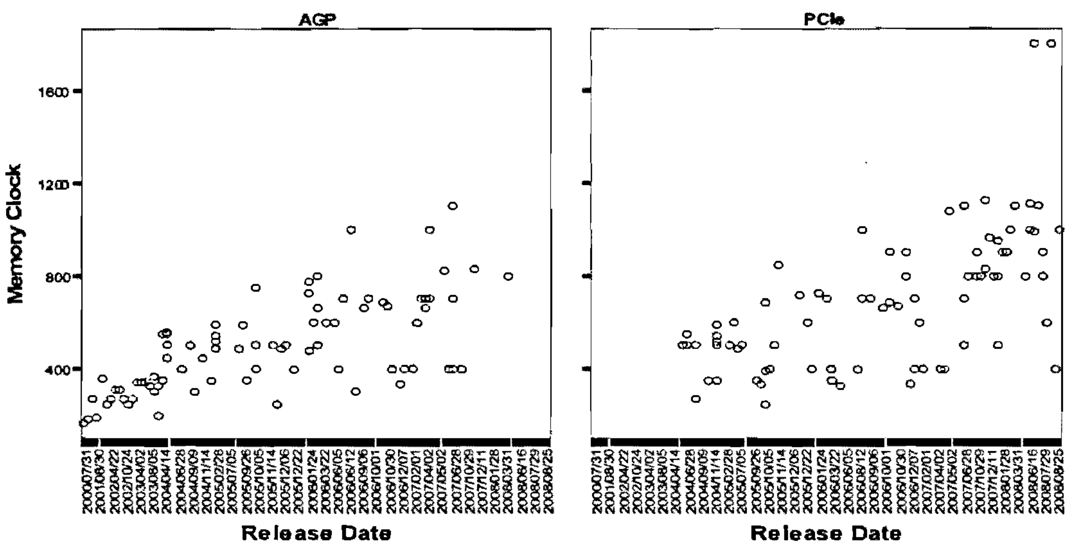

Figure 6: Scatterplot of Memory Clock (in MHz) over Release Date, AGP vs. PCIe, gpuReviewFiltered.sav (GPUReview, 2008)

Control Variables			Release Date	Memory Clock
Bus Architecture	Release Date	Correlation	1.000	.607
		Significance (1-tailed)	.	.000
		df	0	168
	Memory Clock	Correlation	.607	1.000
		Significance (1-tailed)	.000	.
		df	168	0

Table 8: Partial Correlation between Memory Clock and Release Date controlling for Bus Architecture

H1.3.1: (Core Clock) Performance increases are associated with price (MSRP) increases

Contrary to H1.3.1, there appears to be no significant association between Core Clock and MSRP for either the AGP or the PCIe buss as evidenced by the following scatter-plots in Figure 7. Indeed, the partial correlation coefficient between Core Clock and MSRP is not significant at the .05 level (Table 9). Therefore H1.3.1 is not supported.

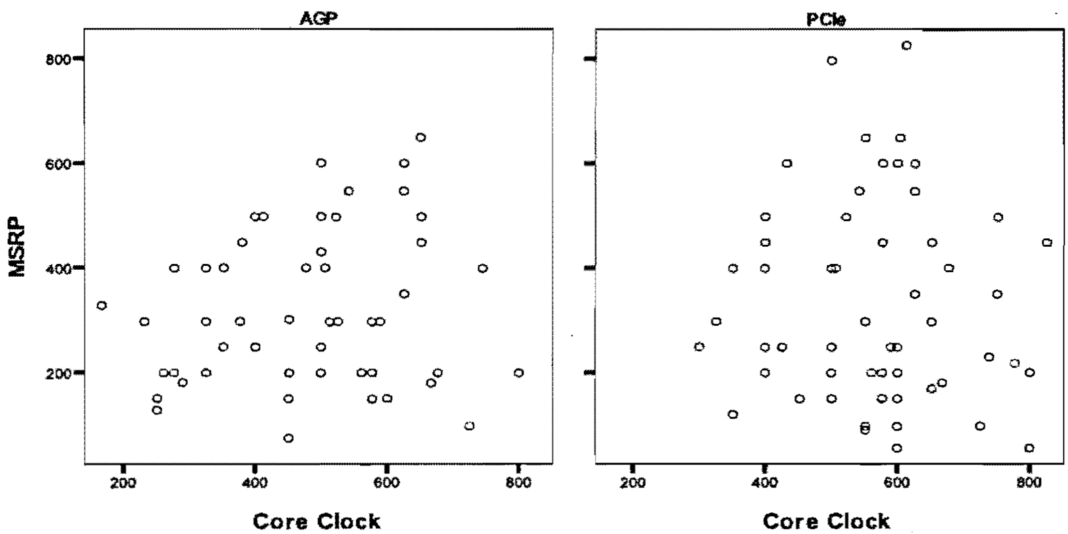

Figure 7: Scatterplot of MSRP (in USD) over Core Clock (in MHz), AGP vs. PCIe, gpuReviewFiltered.sav (GPUReview, 2008)

Control Variables			Core Clock	MSRP
Bus Architecture	Core Clock	Correlation	1.000	.034
		Significance (1-tailed)	.	.359
		df	0	117
	MSRP	Correlation	.034	1.000
		Significance (1-tailed)	.359	.
		df	117	0

Table 9: Partial Correlation between MSRP and Core Clock controlling for Bus Architecture

H1.3.2: (Memory Clock) Performance increases are associated with price (MSRP) increases

No clear association between Memory Clock and MSRP for either the AGP or the PCIe bus is apparent either (Figure 8). However, the positive association between Memory Clock and MSRP is somewhat weak (coefficient = .3) but significant at the .005 level (Table 10). Therefore H1.3.2 is supported.

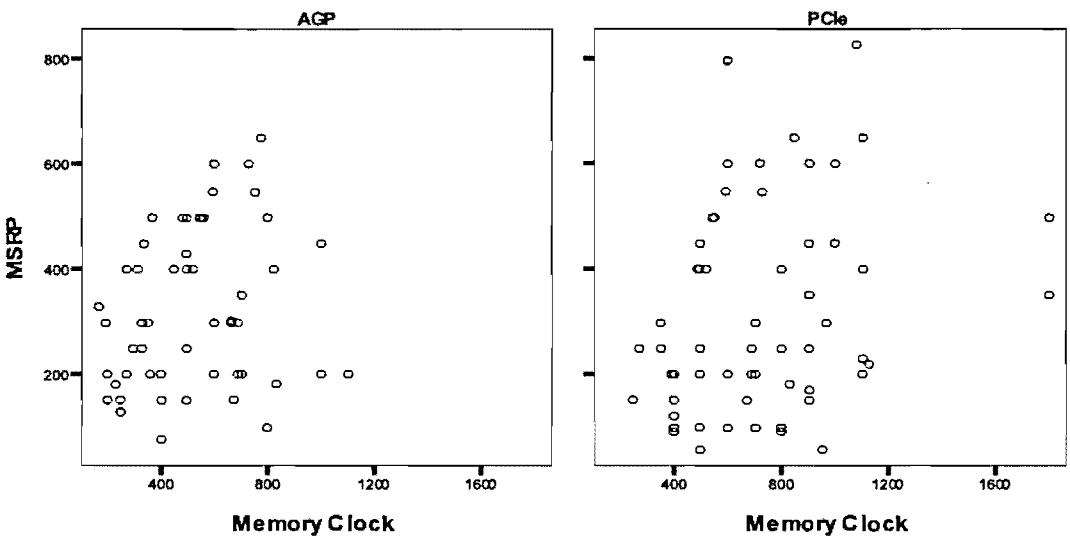

Figure 8: Scatterplot of MSRP (in USD) over Memory Clock (in MHz), AGP vs. PCIe, gpuReviewFiltered.sav (GPUReview, 2008)

Control Variables			Memory Clock	MSRP
Bus Architecture	Memory Clock	Correlation	1.000	.265
		Significance (1-tailed)	.	.002
		df	0	117
	MSRP	Correlation	.265	1.000
		Significance (1-tailed)	.002	.
		df	117	0

Table 10: Partial Correlation between MSRP and Memory Clock controlling for Bus Architecture

H3.1 AGP and PCIe advertised functional performance measures are equally likely to meet customers' functional thresholds.

On average, PCIe based graphics cards appear to be newer and faster in term of Core Clock and Memory Clock (as well as Memory Bandwidth, which usually is not explicitly advertised on product packaging, but is available from manufacturers' web-sites and other product descriptions) (Table 11).

	Bus Architecture	N	Mean	Std. Deviation	Std. Error Mean
Core Clock	AGP	132	419.27	132.237	11.510
	PCIe	92	529.61	126.588	13.198
Memory Clock	AGP	132	422.48	195.320	17.000
	PCIe	92	654.13	298.441	31.115
Memory Bandwidth in GB/s	AGP	132	19.9938	16.63083	1.44753
	PCIe	92	40.9221	36.84534	3.84139
MSRP	AGP	57	326.70	150.916	19.989
	PCIe	63	317.21	189.130	23.828
Release Date	AGP	90	05/04/01	650 20:22:19	68 14:31
	PCIe	81	06/10/24	462 08:52:03	51 08:59

Table 11: Mean Performance Indicators, MSRP and Release Dates between AGP and PCIe based AIB's, gpuReviewFiltered.sav (GPUReview, 2008)

The t-tests for the difference in means confirm this impression. PCIe cards are indeed newer (confidence interval = 99%) and are more likely to meet or exceed (confidence interval = 99% for all three performance indicators) customers' functional thresholds compared to AGP cards (Table 12). Therefore, H3.1 is rejected. Given the higher means for PCIe, PCIe advertised functional measures are more likely to meet customers' functionality thresholds compared to AGP.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Core Clock	Equal variances assumed	.248	.619	-6.252	222	.000	-110.336	17.649	-145.117	-75.555
	Equal variances not assumed			-6.301	201.210	.000	-110.336	17.512	-144.866	-75.806
Memory Clock	Equal variances assumed	15.148	.000	-7.021	222	.000	-231.653	32.995	-296.677	-166.630
	Equal variances not assumed			-6.534	144.497	.000	-231.653	35.456	-301.733	-161.573
Memory Bandwidth in GB/s	Equal variances assumed	27.125	.000	-5.744	222	.000	-20.92827	3.64349	-28.10852	-13.74802
	Equal variances not assumed			-5.098	117.039	.000	-20.92827	4.10507	-29.05812	-12.79841
MSRP	Equal variances assumed	3.094	.081	.302	118	.763	9.495	31.452	-52.789	71.780
	Equal variances not assumed			.305	116.236	.761	9.495	31.102	-52.105	71.096
Release Date	Equal variances assumed	9.930	.002	-6.552	169	.000	-571 09:41	87 05:10	-744	-399
	Equal variances not assumed			-6.667	160.614	.000	-571 09:41	85 17:01	-741	-402

Table 12: Equality of Means Test for AGP vs. PCIe Performance Indicators, MSRP and Release Date, gpuReviewFiltered.sav (GPUReview, 2008)

Notice that H3.1 is stated as a null hypothesis. The t-test is used to test the hypothesis that the two architectures (AGP vs. PCIe based AIB's) do not significantly differ in terms of readily quantifiable measures of performance (core clock, memory clock and memory bandwidth), price (MSRP) and novelty (release date). Indeed, the demand heterogeneity theory does not assert that PCIe based cards, for example, perform better, are newer, or cost more compared to AGP based cards (and vice versa). Therefore, assuming no difference and testing the null hypothesis directly using the 2-tailed t-test is appropriate.

However, the described statistical procedure only allows for the null hypothesis to be rejected but not proven. That is, if null is rejected, the conclusion for H3.1 is that advertised functional performance means are not the same for the two architectures (and therefore are not equally likely to meet customers' functional thresholds in terms of measures given above). By extension, the architecture with the higher functional performance means is deemed more likely to meet customers' functional performance thresholds. If the null cannot be rejected, the appropriate conclusion is that there is no reason to believe that the two architectures are significantly different in terms of indicated measures, but not that they are the same. This same logic is applied throughout the paper whenever a null hypothesis was tested directly using the t-test procedure.

H4.1 AGP and PCIe are equally likely to meet customers' net utility thresholds.

Concluding from the t-test procedure in Table 12, PCIe AIB's are more likely to meet customers' functionality thresholds compared to AGP AIB's (H3.1). Since utility thresholds capture the interaction between functional thresholds and price, an additional test (H4.2) is required.

H4.2 AGP and PCIe do not differ significantly in average price.

From the same t-test analysis described in Table 12 it is clear that AGP and PCIe do not differ significantly in average price (the test for difference in means is not significant at the 95% confidence interval). Therefore H4.2 is supported.

Considering H3.1 and H4.2 jointly, H4.1 is rejected: PCIe cards are more likely to meet customers' functionality thresholds. This is true because PCIe cards perform significantly better than AGP (H3.1) at around the same price (H4.2).

The inclusion of switching costs involved in switching from AGP to PCIe may alter the utility threshold conclusion in 4.1. Namely, switching to PCIe necessitates the purchase of a new PCIe-enabled motherboard, which also requires a new CPU, memory and often a power supply. In that case, the greater average advertised performance of PCIe would be offset by the far greater switching costs involved. That is, the net utility threshold advantage of PCIe compared to AGP is likely to disappear. Unfortunately, data on actual switching costs is not available so that it is not possible to test the implications of switching costs on net utility thresholds in this research.

Claim 2: Product innovations feature Overall Performance increases at Stable Prices.

In order to conclusively evaluate Adner and Levinthal's claim that consumers experience increasing product performance at relatively stable prices, it is necessary do develop a better measure for AIB graphics cards product performance. Core and memory speeds alone do not adequately capture the overall performance of graphics cards. A better indicator involves a more complex interaction of these two factors as well as Memory Bandwidth. The real performance that consumers actually experience depends on the AIB graphics card hardware and the software environment in which these components operate (drivers, operating system, and application and PC game software). It is beyond the scope of this research to adequately assess the real overall performance for each card in the GPUReview database. Nevertheless, a more accurate indicator of overall performance can be derived from the available data.

A new construct of Overall Performance is derived to capture the interaction of Core Clock, Memory Clock and Memory Bandwidth by taking the natural logarithm of the product of each of these indicators. Multiplying the contributing factors to obtain an interaction term (Overall Performance) is an appropriate technique in statistical procedures when the researcher is led to believe that an interaction between variables might exist. The assumption here is that the advertised performance measures indeed interact with each other to impact on the overall performance of a graphics card. The natural logarithm preserves the relative differences in intervals between obtained values of the interaction term but reduces the absolute range of all possible values, making them more manageable. In other words, this new construct better approximates the real performance of a graphics card short of doing "real life" performance tests, because it takes into consideration all advertised performance measures (i.e. core clock, memory clock, memory bandwidth). The Overall Performance construct thus adds to our understanding of the real performance of a video card consumers experience compared than any single advertised performance measure alone. Overall Performance is derived as follows:

*Overall Performance = ln (Core Clock * Memory Clock * Memory Bandwidth)*

The resulting synthetic scores are normally distributed (Figure 9), where the mean = 15.2, median = 15.3 and mode = 15.9 are reasonably close to each other, and range from 11.5 for the lowest performing cards to 19.6 for the highest performing cards (Table 13).

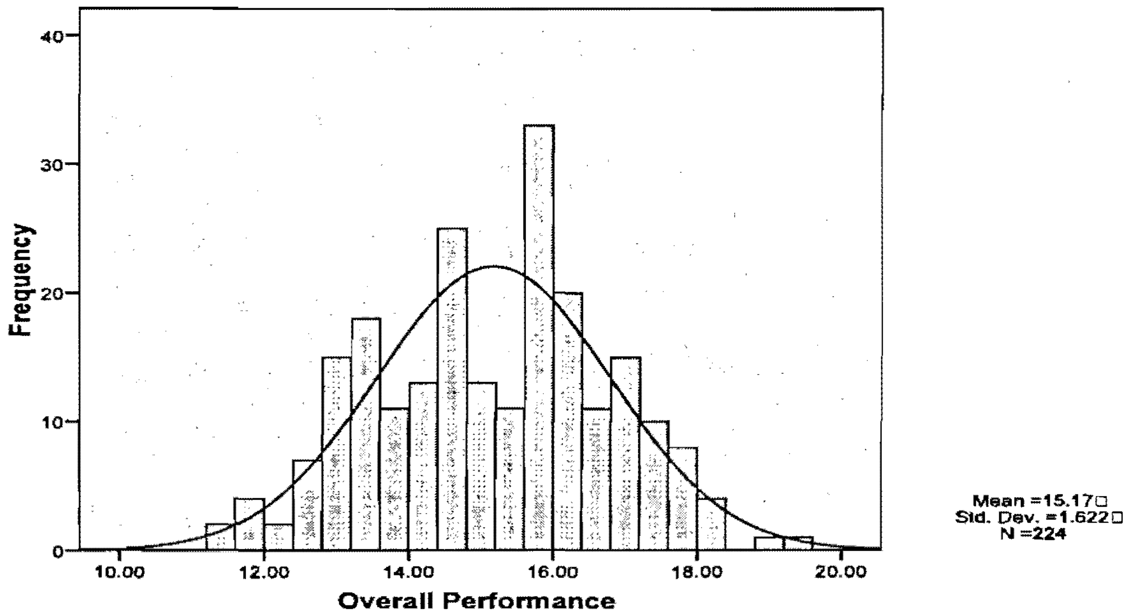

Figure 9: Normal Distribution of Overall Performance Scores, AGP and PCIe, gpuReviewFiltered.sav sample (GPUReview, 2008)

N	Valid	224
	Missing	0
Mean		15.1733
Median		15.2671
Mode		15.89
Std. Deviation		1.62189
Minimum		11.49
Maximum		19.56

Table 13: Overall Performance Descriptive Statistics, AGP and PCIe, gpuReviewFiltered.sav (GPUReview, 2008)

H1.2.3 Product Innovations are associated with Overall Performance increases

The scatter plot in Figure 10 again suggests that newer AIB graphics cards have been performing better in both groups. As expected, there is a moderate positive correlation (coefficient = .59) between Release Date and Overall Performance (Table 14). H1.2.3 is thus supported; novel products perform better overall.

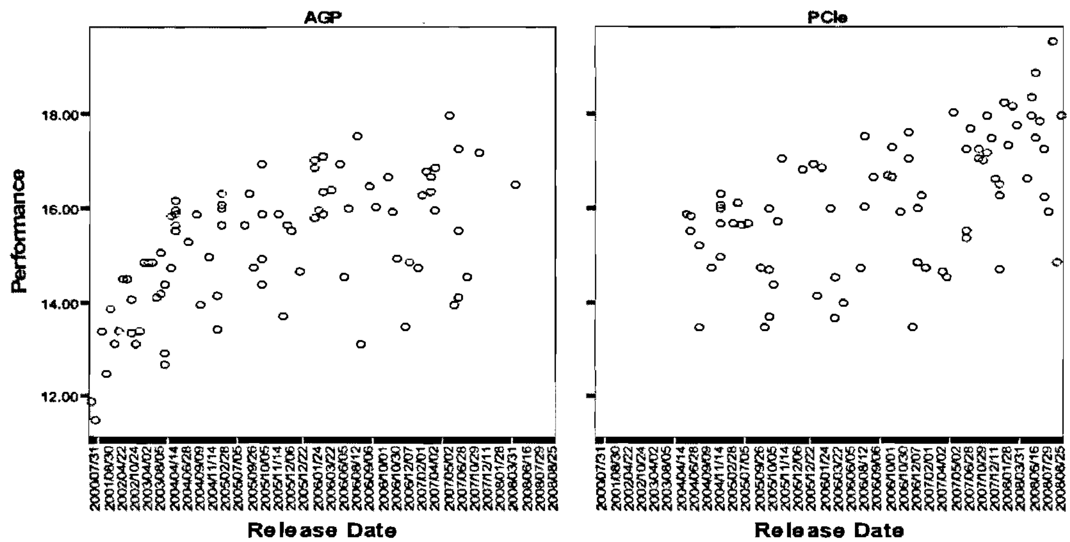

Figure 10: Scatterplot of Overall Performance Scores over Release Date, AGP vs. PCIe, gpuReviewFiltered.sav (GPUReview, 2008)

Control Variables			Overall Performance	Release Date
Bus Architecture	Overall Performance	Correlation	1.000	.587
		Significance (1-tailed)	.	.000
		df	0	168
	Release Date	Correlation	.587	1.000
		Significance (1-tailed)	.000	.
		df	168	0

Table 14: Partial Correlation between Overall Performance and Release Date controlling for Bus Architecture

H1.3.3: Overall Performance increases are associated with price increases

However, it is also true that performance increases demanded higher prices in both categories as shown in Figure 11. In fact, there is a moderately strong (coefficient = 0.46) positive association between price and performance for both, AGP and PCIe base AIB graphics cards (Table 15). H1.3.3 is thus also supported.

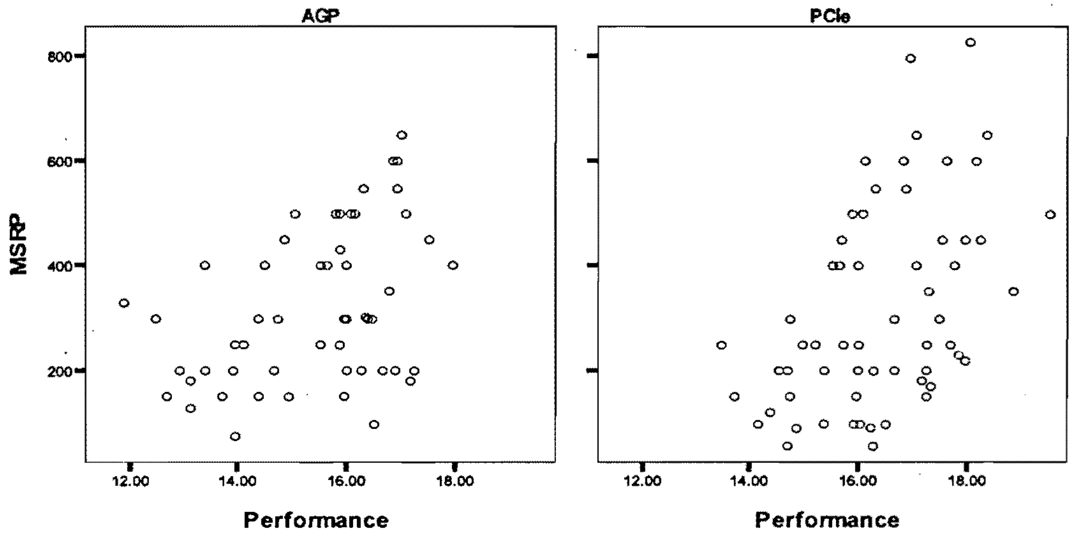

Figure 11: Scatterplot of MSRP (in USD) over Overall Performance Scores, AGP vs. PCIe, gpuReviewFiltered.sav (GPUReview, 2008)

Control Variables			Overall Performance	MSRP
Bus Architecture	Overall Performance	Correlation	1.000	.455
		Significance (1-tailed)	.	.000
		df	0	117
	MSRP	Correlation	.455	1.000
		Significance (1-tailed)	.000	.
		df	117	0

Table 15: Partial Correlation between MSRP and Overall Performance controlling for Bus Architecture

Such correlation was to be expected. It is reasonable to assume that, in general, newer technologies offer performance increases but also demand higher prices. This is not surprising were it not contrary to the demand heterogeneity theory's claim that consumers experience stable prices over performance increases. However, the demand heterogeneity theory only claims that within any given price range, which can be deemed constant (stable) over time, consumers still experience performance increases. To test this claim, a narrower MSRP range for the available data needs to be selected and held constant so as to be able to evaluate whether consumers indeed experience performance increases within a given price segment.

Looking at the initial MSRP distribution for both the AGP and PCIe categories (see Appendix II: Price, release date and performance indicators distributions of products in the 'GPUReview' data set), the narrow price range around the modal MSRP of $199 USD is selected. The MSRP mode as a point of reference is appropriate as it refers to the greatest number of AIB graphics cards in the database. It is reasonable to assume that the price segment around the modal MSRP also constitutes the chief segment which manufacturers are targeting in their product offering.

The price range of $140 - $260 (with ca. $200 being the modal value) has been chosen for practical purposes: looking at the price frequency table it was apparent that a number of cards in the database (gpuReviewFiltered.sav) were priced at $149 and that they would not be captured by a narrower but more obvious MSRP range of $150 – $250. Therefore, this range was expanded to include a wider price differential of $120 centered on the modal price of $200. This range is wide enough to capture a sufficient number of data points and thus lend more validity and accuracy to the statistical procedures, yet narrow enough given the absolute MSRP range of $55 - $829 (see MSRP frequencies, Figure 16). Its lower range ($150) is high enough to include the majority of the AIB graphics cards targeting the enthusiast segment yet its upper range ($260) is low enough so as to capture the majority of consumers in general.

Therefore, a new dataset "gpuReviewFiltered140-260msrp.sav" was created containing only the MSRP segment of interest, which included 21 AGP and 24 PCIe cards (Table 16). Given the relatively small N=45 for this narrower sample set, confidence in the next findings must not be overstated.

	N	Minimum	Maximum	Mean	Std. Deviation
Release Date	44	2002/01/22	2008/07/29	2006/04/04	530 21:32:13.540
MSRP	45	149	249	199.22	35.643
Overall Performance	45	12.68	17.96	15.5160	1.45337
Valid N (listwise)	44				

Table 16: Descriptive Statistics for Release Date, MSRP and Overall Performance Score in the"gpuReviewFiltered140-260msrp.sav" SPSS dataset (GPUReview, 2008)

H2: Product innovations feature Overall Performance increases at Stable Prices

The scatterplot in Figure 12 clearly shows that the Overall Performance has been increasing over time for both categories within the fixed MSRP segment of choice. In other words, consumer did in fact experience strong (coefficient = 0.82) Overall Performance increases over time at relatively stable prices ranging from MSRP $140 to $260 (Table 17). Therefore, H2 is supported.

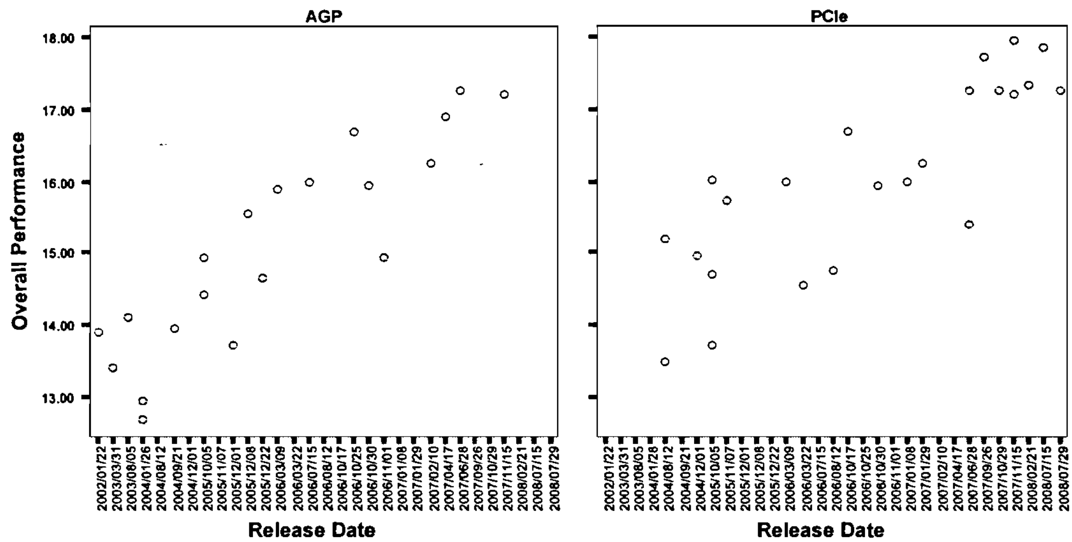

Figure 12: Scatterplot of Overall Performance Scores over Release Date @ Stable Prices, AGP vs. PCIe, gpuReviewFiltered140-260msrp.sav (GPUReview, 2008)

Control Variables			Overall Performance	Release Date
Bus Architecture	Overall Performance	Correlation	1.000	.827
		Significance (2-tailed)	.	.000
		df	0	41
	Release Date	Correlation	.827	1.000
		Significance (2-tailed)	.000	.
		df	41	0

Table 17: Partial Correlation between Overall Performance and Release Date @ Stable Prices controlling for Bus Architecture

H2.1: Overall Performance increases are associated with price increases even within a narrower price range

On the other hand, it is not at all obvious that higher performances demanded higher prices (Figure 13). The partial correlation in Table 18 confirms that within this sample set, the association between Overall Performance and MSRP is weak and insignificant. Therefore, H2.1 is rejected: there is no association between Overall Performance and MSRP within a narrow price range. This should not be surprising at all, since the price range for this data set has been fixed by definition and is assumed stable.

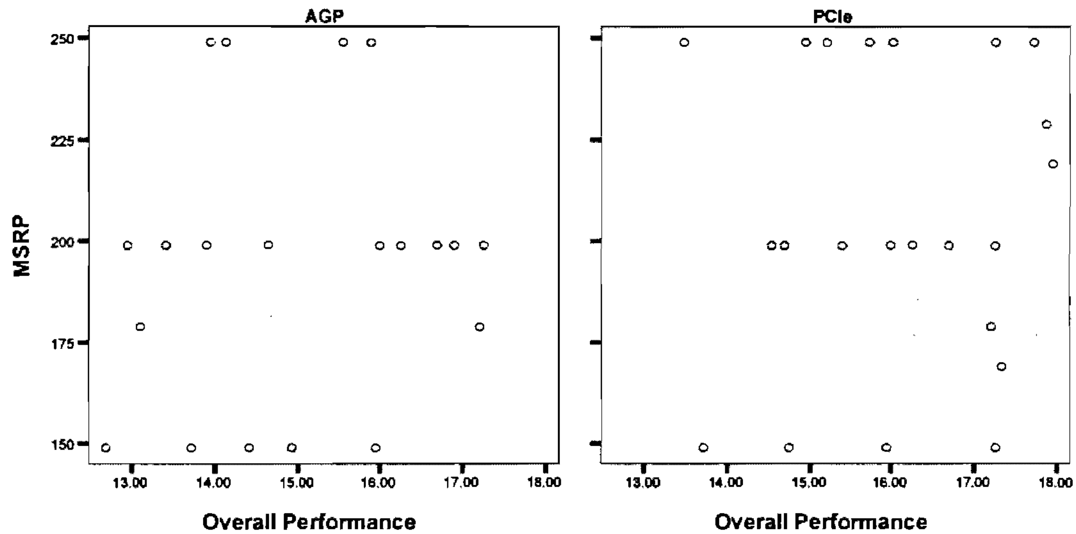

Figure 13: Scatterplot of MSRP (in USD) over Overall Performance Scores @ Stable Prices, AGP vs. PCIe, gpuReviewFiltered140-260msrp.sav (GPUReview, 2008)

Control Variables			Overall Performance	MSRP
Bus Architecture	Overall Performance	Correlation	1.000	.096
		Significance (2-tailed)	.	.534
		df	0	42
	MSRP	Correlation	.096	1.000
		Significance (2-tailed)	.534	.
		df	42	0

Table 18: Partial Correlation between Overall Performance and MSRP @ Stable Prices controlling for Bus Architecture

H4.3: AGP and PCIe are equally likely to meet customers' net utility thresholds at stable prices

Comparing the two architectures within the price segment centering on the modal MSRP, it appears that on average PCIe cards were newer, still cost somewhat more, and feature higher performance measures (Table 19).

	Bus Architecture	N	Mean	Std. Deviation	Std. Error Mean
MSRP	AGP	21	192.33	35.261	7.695
	PCIe	24	205.25	35.608	7.268
Core Clock	AGP	21	473.95	152.463	33.270
	PCIe	24	556.92	119.768	24.448
Memory Clock	AGP	21	496.81	256.938	56.069
	PCIe	24	652.63	263.900	53.868
Memory Bandwidth in GB/s	AGP	21	20.2682	14.23283	3.10586
	PCIe	24	34.6080	24.74383	5.05081
Overall Performance	AGP	21	14.9697	1.44567	.31547
	PCIe	24	15.9940	1.30866	.26713
Release Date	AGP	20	05/09/14	576 15:41:26	128 22:38
	PCIe	24	06/09/20	432 01:32:01	88 04:40

Table 19: Mean MSRP, Performance Indicators, Overall Performance Score and Release Date @ Stable Prices, AGP and PCIe, gpuReviewFiltered140-260msrp.sav (GPUReview, 2008)

As expected, the difference in average prices of PCIe based graphics cards compared to AGP based graphics cards was not significant. The difference in Overall Performance was significant at the 0.05 level (Table 20). Therefore H4.3 is rejected. PCIe offers greater net utility to customers. As mentioned before, the inclusion of switching cost considerations might change this balance in AGP's favor as the total cost of selecting PCIe would exceed the assumed constant price.

H3.2 AGP and PCIe advertised functional performance measures are equally likely to meet customers' functional thresholds at stable prices

In terms of clock speeds the result are mixed; Core Clock differences are barely significant,, depending on the equal variances assumption, while Memory Clock differences are just short of the 0.05 significance level (Table 20). The results for H3.2 are therefore mixed in terms of advertised functional performance indicators. However, PCIe is more likely to meet customers' functionality thresholds taking Overall Performance into account (significant at the .05 level, see Table 20).

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
MSRP	Equal variances assumed	.047	.830	-1.219	43	.229	-12.917	10.592	-34.277	8.444
	Equal variances not assumed			-1.220	42.318	.229	-12.917	10.585	-34.273	8.439
Core Clock	Equal variances assumed	2.077	.157	-2.042	43	.047	-82.964	40.625	-164.892	-1.037
	Equal variances not assumed			-2.009	37.837	.052	-82.964	41.287	-166.557	.628
Memory Clock	Equal variances assumed	.140	.710	-2.000	43	.052	-155.815	77.895	-312.905	1.274
	Equal variances not assumed			-2.004	42.486	.051	-155.815	77.753	-312.674	1.043
Memory Bandwidth in GB/s	Equal variances assumed	5.863	.020	-2.337	43	.024	-14.33981	6.13615	26.71454	-1.96508
	Equal variances not assumed			-2.418	37.514	.021	-14.33981	5.92934	26.34824	-2.33138
Overall Performanc	Equal variances assumed	.562	.458	-2.495	43	.017	-1.02430	.41059	-1.85233	-.19627
	Equal variances not assumed			-2.478	40.747	.017	-1.02430	.41338	-1.85929	-.18931
Release Date	Equal variances assumed	1.208	.278	-2.443	42	.019	-371 19:00	152 04:27	-679	-64 16:03
	Equal variances not assumed			-2.380	34.666	.023	-371 19:00	156 05:17	-689	-54 12:56

Table 20: Equality of Means Test @ Stable Prices for MSRP, Performance Indicators, Overall performance Score, and Release Date, AGP vs. PCIe, gpuReviewFiltered140-260msrp.sav (GPUReview, 2008)

It seems that the Overall Performance advantage of PCIe cards in this price range is mainly due to the significantly higher Memory Bandwidth of the same. This is to be expected, since the emergence of the PCIe innovation is an architectural data bus innovation aimed at increasing the data bandwidth compared to the older AGP buss design. In effect, the PCIe bus offers more "highway lanes" for data to commute from the motherboard CPU and RAM memory to the add-in-board GPU and graphics memory.

In terms of GPU and memory clock frequencies the two AIB graphics cards designs are still on par in this important price segment. Does the higher PCIe thru-output offer enough incentives for consumers to switch to the new architecture, and how quickly will they abandon the older architecture?

5.2 Qualitative Analysis

The Useful Reviews sample constitutes two sets (AGP & PCIe) of 15 product reviews each that were deemed "useful" by the greatest number of external readers in each category. Each review is further subdivided into "pro" and "cons" statements. It is assumed that useful product feedback is most likely to contain information that is meaningful to consumers that are making the decision to purchase or not to purchase a given product. The two sets of data were coded for content, whereby the coding scheme was partially imposed by the demand heterogeneity and network externalities theory and in part emerged from the text itself. Again, the number of data points is not large, so that certainty about the findings should be reserved. Nevertheless, this effort offers some insight into the qualitative attributes of the demand context in which the technologies in question are evaluated.

5.2.1 "Pro" Comments

The chart in Figure 14 represents "pro" statements for both bus architecture categories and shows the corresponding coded constructs that apply, sorted in order of total descending frequencies.

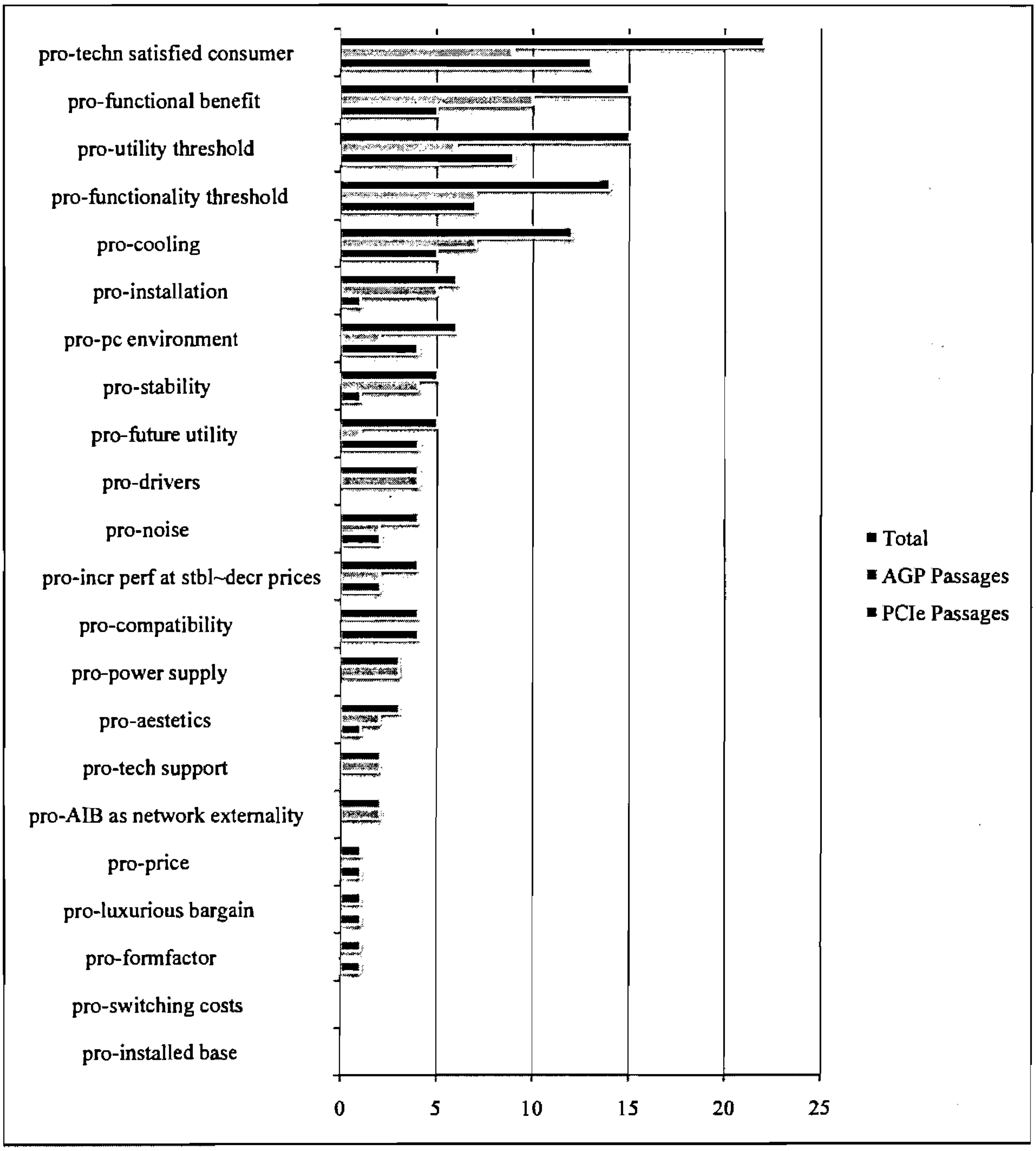

Figure 14: Frequency of "Pro" Coded Constructs, descending, AGP and PCIe, "Useful Reviews Sample" (newegg.com, 2008)

According to the feedback statements left by product reviewers, the greatest number of "pro" coded passages:

1. Affirmed that the reviewers are *technologically satisfied* with the products under review.

2. Approved of the *functional benefits* the reviewers derived in excess of their *functional requirements* from the products under review.

3. Affirmed that reviewers' *utility threshold* was not exceeded, that is, the product price was below the highest price reviewers were willing to pay for products that meet their *minimum performance requirements.*

4. Affirmed that reviewers' *functionality threshold* was met or exceeded, that is, the product met or exceeded reviewers' *minimum performance requirements.*

5. Approved of the *cooling* solution to the products under review.

Coded passages that occurred with some frequency in users' "pro" reviews include approval of product:

6. Hardware and software *installation* process.

7. Interaction within reviewers' existing *PC environment* (hardware/software).

8. Performance *stability.*

9. Projected *future utility*, that is, the potential that the product will continue to meet reviewers' *functional requirements* or exceed them, thus offering further *functional benefits* in the future.

10. Software *drivers* needed for proper and efficient operation.

11. Generated *noise* levels.

12. *Price stability or decrease* while meeting or exceeding reviewers' *functional requirements.*

13. *Compatibility* with reviewers' existing hardware/software.

14. *Power supply* requirements.

15. *Aesthetics*, both physical appearance and product generated aesthetics (picture quality).

16. Manufacturers customer and *technical support.*

Coded passages that occurred with least frequency in users' "pro" reviews include approval of product:

17. *Form-factor*, that is, the physical fitness into users' hardware *PC environment.*

18. Serving as a *network externality* with respect to reviewers' *PC environment*, that is, the product is serving to prolong the life-cycle of the aging PC system or enhancing the functionality of the existing system.

19. *Price* without relating it to product functionality or performance.

20. Constituting a *luxurious bargain*; a reference to product's seemingly unlimited exogenous functional performance in the subjective assessment of reviewers, while acknowledging that the product price does not exceed reviewers' willingness to pay for such performance.

Interestingly, any implicit references to *switching costs* or the *installed base* -both central constructs in the dominant theory of technology evolution in management literature- are absent from "pro" coded passages in the "useful reviews" sample.

An overview of "pro" coded passage frequencies is provided in Table 21.

Coded Construct	Total Passages	AGP Passages	PCIe Passages
pro-techn. satisfied consumer	17.1%	7.0%	10.1%
pro-utility threshold	11.6%	4.7%	7.0%
pro-functional benefit	11.6%	7.8%	3.9%
pro-functionality threshold	10.9%	5.4%	5.4%
pro-cooling	9.3%	5.4%	3.9%
pro-pc environment	4.7%	1.6%	3.1%
pro-installation	4.7%	3.9%	0.8%
pro-future utility	3.9%	0.8%	3.1%
pro-stability	3.9%	3.1%	0.8%
pro-compatibility	3.1%	0.0%	3.1%
pro-incr perf at stbl~decr prices	3.1%	1.6%	1.6%
pro-noise	3.1%	1.6%	1.6%
pro-drivers	3.1%	3.1%	0.0%
pro-aesthetics	2.3%	1.6%	0.8%
pro-power supply	2.3%	2.3%	0.0%
pro-AIB as network externality	1.6%	1.6%	0.0%
pro-tech support	1.6%	1.6%	0.0%
pro-formfactor	0.8%	0.0%	0.8%
pro-luxurious bargain	0.8%	0.0%	0.8%
pro-price	0.8%	0.0%	0.8%
pro-installed base	0.0%	0.0%	0.0%
pro-switching costs	0.0%	0.0%	0.0%

Table 21: Percentages of Coded Constructs implying Customer Approval, descending, AGP & PCIe, "Useful Reviews Sample" (newegg.com, 2008)

H5: Consumers express that they are technologically satisfied

The qualitative evidence suggests that the majority of "pro" passages involve self-reported technological satisfaction with both graphics card categories. The evidence is somewhat stronger for PCIe based AIB'. This is consistent with quantitative findings that PCIe cards are more likely to exceed consumers' functional thresholds (see H3.1) and thus produce technologically satisfied consumers.

H4: Consumers express approval for products that meet their net utility thresholds

Similarly, PCIe based graphics cards are more likely to meet consumers' net utility thresholds compared to AGP. Support for net utility thresholds within AGP "pro" passages is ranked fifth. Overall, consumers do voice support for products meeting their utility thresholds, but more so in the case of PCIe, which is consistent with quantitative findings (H4.1).

H6: Consumers express approval for products that offer functional benefits

On the other hand, more AGP passages approve of functional benefits compared to PCIe. This is the most often mentioned item in the AGP category. It seems that AGP users derive more functional benefit from their cards in excess of what they have bargained for. For PCIe, this item is ranked fourth. The evidence for H6 is stronger for AGP than PCIe in terms of self-reported approval of functional benefits.

H3: Consumers express approval for products that meet their functionality thresholds

There is no difference between AGP and PCIe in terms of the number of passages approving the fact that the product has met consumers' functionality thresholds. This is inconsistent with H3.1, the finding that PCIe reviewers are more likely to do so. Nevertheless, this item features prominently in both categories.

H7: Consumers express approval for luxurious bargains

The luxurious bargain item is featured equally in both categories but is not very prominent. There is not enough evidence to support this hypothesis.

In general, the qualitative analysis found that there was strong support for H3 (functionality threshold), H4 (utility threshold), H5 (technologically satisfied consumers), and H6 (functional benefit). PCIe was favored in most instances except for H6 (functional benefit). Support for H7 (luxurious bargain) was very weak. Switching costs and installed base issues were not explicitly mentioned in the reviews.

On the other hand, issues pertaining mostly to network externalities, such as driver support, PC environment, cooling solutions, ease of installation, compatibility, aesthetic considerations, and power supply adequacy were mentioned with fair frequency.

5.2.2 "Cons" Comments

The chart in Figure 15 represents "cons" statements for both bus architecture categories and shows the corresponding coded constructs that apply, sorted in order of total descending frequencies.

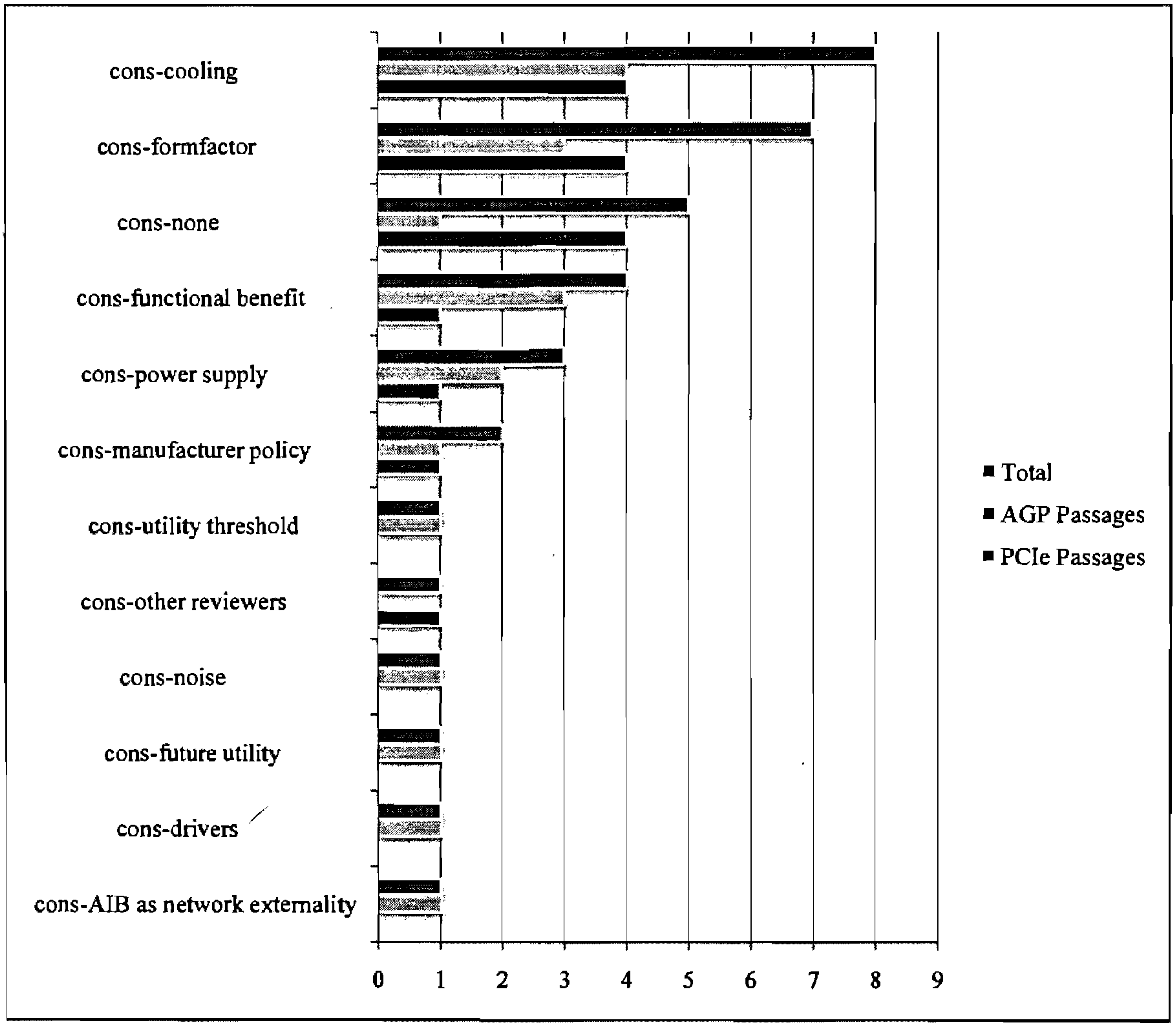

Figure 15: Frequency of "Cons" Coded Constructs, descending, AGP and PCIe, "Useful Reviews Sample" (newegg.com, 2008)

According to the feedback statements left by consumer reviewers, the greatest number of "cons" coded passages:

1. Disapproved of the *cooling* solution to the products under review.

2. Disapproved of the *form-factor*, that is, the physical fitness into users' hardware *PC environment*.

3. Explicitly stated that there were no objections to the product whatsoever (inverse "pro" code)

Coded passages that occur with some frequency in users' "cons" reviews disapproved of:

4. The lack of anticipated *functional benefits* the reviewers did not derive in excess of their *functional requirements* from the products under review.

5. Products' *power supply* requirements.

6. Manufacturers customer and *technical support.*

Coded passages that occurred with least frequency in users' "cons" reviews:

7. Complained that reviewers' *utility threshold* was exceeded, that is, the product price was above the highest price reviewers were willing to pay for products that do not entirely meet their *performance requirements.*

8. Disapproved of other reviewers.

9. Disapproved of the generated *noise* levels.

10. Disapproved of the projected *future utility*, that is, the assessment that the product will not continue to meet reviewers' *functional requirements* or exceed them, thus failing to offer further *functional benefits* down the road.

11. Disapproved of software *drivers* needed for proper and efficient operation.

12. Dismissed the product as a *network externality* with respect to reviewers' *PC environment*, that is, the product itself as not serving to prolong the life-cycle of the aging PC system or enhancing the functionality of the existing system.

An overview of "cons" coded passage frequencies is provided in Table 22.

Coded Construct	Total Passages	AGP Passages	PCIe Passages
cons-cooling	22.9%	11.4%	11.4%
cons-formfactor	20.0%	8.6%	11.4%
cons-none	14.3%	2.9%	11.4%
cons-functional benefit	11.4%	8.6%	2.9%
cons-power supply	8.6%	5.7%	2.9%
cons-manufacturer policy	5.7%	2.9%	2.9%
cons-utility threshold	2.9%	2.9%	0.0%
cons-other reviewers	2.9%	0.0%	2.9%
cons-noise	2.9%	2.9%	0.0%
cons-future utility	2.9%	2.9%	0.0%
cons-drivers	2.9%	2.9%	0.0%
cons-AIB as network externality	2.9%	2.9%	0.0%

Table 22: Percentages of Coded Constructs implying Customer Disapproval, descending, AGP & PCIe, "Useful Reviews Sample" (newegg.com, 2008)

The greatest number of passages dealt with cooling and form-factor issues and both problems were equally represented for APG and PCIe. Many review passages, on the other hand, found nothing wrong with the products, but this is particularly true for the PCIe category.

The lack of functional benefits, power supply, and manufacturer policy issues were also widely reported but more so for AGP than PCIe. The finding in terms of functional benefit here mitigates the opposite finding in the 5.2.1 "pro" comments section.

Problems concerning utility thresholds and future potential utility of the product, as well as noise and driver issues were somewhat reported for AGP but not at all for PCIe. A small percentage of passages referred to the fact that AGP does not serve as a network externality for the overall PC system in a sense that AGP does not extend the performance and utility of the overall system. Similarly, a small percentage of PCIe passage complained about other reviewers. Overall, the last six constructs were not sufficiently represented in user "cons" reviews.

A note of caution is in order at this point. The qualitative portion of this analysis rests on a fairly small sample size and thus confidence in its findings must be guarded. The generalizability to the wider population (in this case, other product reviews) is not asserted nor can be claimed. In other words, the qualitative findings might be due to chance alone. Furthermore, as mentioned in section 4.2, this is a highly selective sample of reviews that other user found most "helpful" (see section 4.2 for the selection rationale), and for that reason alone cannot be deemed representative of the wider population of product reviews. Nevertheless, the qualitative analysis does offer some means of assessing the major claims of the theory, provided that the reader and researcher are aware of stated confidence and generalizability limitations.

5.3 Summary of Findings

Table 23 provides an overview of the findings which are discussed in the next section. Although empirical conclusions to the various demand heterogeneity theory claims are stated as "supported" or "no support" in this table, none of these conclusion imply absolute certainty (in a sense that any given claim is 100% true or false). This format was selected for the sake of brevity and quick overview, as well as to guide the discussion and conclusion in the next section. For exact strength of associations and likelihoods, as well as their corresponding confidence level, the reader is referred to the finding and analysis section. Moreover, qualitative evidence, while present for some claims, reflects simple counting of qualitative categories, that is, their prevalence. The strength of qualitatively examined claims could not be ascertained with the method used nor does this research imply any particular degrees of confidence with respect to the same. Again, certainty about these conclusions must be reserved. However, qualitative methods are rarely employed to ascertain the *strength* of theoretical claims, as much as they are employed to ascertain the *presence* and *essence* of theoretical claims. Nevertheless, an effort has been made to augment qualitatively derived conclusions with quantitatively derived ones where data was present and suitable (for example, see heterogeneous thresholds claims in Table 23). Fields marked with 'x' imply that the qualitative/quantitative data does not exist with respect to the particular claim. The third column implies preference for AGP vs. PCIe AIB's based on the empirical findings in the first two columns where appropriate. This is an attempt to answer the question of AGP's longevity when faced with the new PCIe architecture.

Demand Heterogeneity Claims	Quantitative Evidence	Qualitative Evidence	AGP vs. PCIe
Competitive Strategy Claims			
Claim 1: Firms continue to engage in product innovation in mature product classes.	supported	x	x
H1.1: Mature product classes (Release Date) are associated with price (MSRP) decreases	supported	x	x
H1.2.1: Product innovations (Release Date) are associated with (Core Clock) performance increases.	supported	x	x
H1.2.2: Product innovations (Release Date) are associated with (Memory Clock) performance increases.	supported	x	x
H1.2.3 Product Innovations (Release Date) are associated with Overall Performance increases.	supported	x	x
H1.3.1: (Core Clock) Performance increases are associated with price (MSRP) increases.	no support	x	x
H1.3.2: (Memory Clock) Performance increases are associated with price (MSRP) increases.	supported	x	x
H1.3.3: Overall Performance increases are associated with price increases.	supported	x	x
Claim 2: Product innovations feature Overall Performance increases at Stable Prices.	supported	x	equal
H2.1: Overall Performance is associated with price increases even within a narrower price range.	no support	x	equal
Heterogeneous Thresholds Claims			
Claim 3: Consumers support products that meet their functionality thresholds.	x	supported	PCIe preferred
H3.1 AGP and PCIe advertised functional performance measures are equally likely to meet customers' functional thresholds.	no support (PCIe wins)	supported	
H3.2 AGP and PCIe advertised functional performance measures are equally likely to meet customers' functional thresholds at stable prices	mixed findings	Equal by self- report	mixed findings

Claim 4: Consumers support products that meet their net utility thresholds.	x	supported (more so for PCIe)	PCIe preferred
H4.1 AGP and PCIe are equally likely to meet customers' net utility thresholds.	no support (PCIe wins), follows from H3.1& H4.2	no support (PCIe wins), by self-report	PCIe preferred
H4.2 AGP and PCIe do not differ significantly in average price.	supported	x	equal
H4.3: AGP and PCIe are equally likely to meet customers' net utility thresholds at stable prices	no support (PCIe wins)	x	PCIe preferred
Technologically Satisfied Consumers Claims			
Claim 5: Consumers are technologically satisfied.	x	supported (more so for PCIe)	PCIe wins
Claim 6: Consumers support products that offer functional benefits.	x	supported	AGP preferred
Claim 7: Consumers support luxurious bargains.	x	Not enough evidence	Equal report

Table 23: Summary of Findings

6 Discussion and Conclusions

A set of seven basic predictions of the demand heterogeneity theory were tested. There was considerable evidence to support the claim that firms engage in product innovation in mature markets and that consumers benefit from increasing technology performance at stable prices. The emergence of technologically satisfied consumers and their appreciation of functional benefits offered by technology were qualitatively confirmed. The case for the emergence of luxurious bargains could not be established.

The theory suggested that the main reasons for the retention of the legacy AGP data interface are due to the fact that it meets or exceeded consumers' functional thresholds and net utility. However, the selection of the novel PCIe interface is also obvious, as it outperforms AGP in both functional performance as well as net utility. One reason why consumers do not flock to the new interface may be due to switching costs, for which there was no qualitative or quantitative data to test. The transition to

PCIe involves not only the purchase of the AIB itself, but also additional compatible hardware upgrades. This additional cost would alter the balance of net utility in AGP's favor. However, the whole point of "sticking' to AGP resides in the fact that consumers are indeed happy with it in terms of functional performance. In fact, while AGP based AIB's do not exceed the functional performance of PCIe based AIB's, they are still somewhat on par with PCIe and they still outstrip the minimum functional requirements of most consumers leading to technologically satisfied consumers.

While it is true that PCIe offers greater functional performance over the entire price segment, under the condition of stable prices, it is not conclusive that PCIe offer greater performance compared to AGP. Both AGP and PCIe based cards offer functional performance increases over time as firms continue to engage in product innovation in the competition for technologically satisfied customers. Customers are not only technologically satisfied, but also aware of their functional and utility thresholds, and of products' functional benefits as evidenced by qualitative data (at least in the case of enthusiast graphics cards users considered in this thesis). Moreover, customers are able to communicate this info to others through internet-enabled means of communication and thus, it is argued, have an influence on others' decision whether or not to purchase.

Both AGP and PCIe cards contain models that by far exceed reasonable functional requirements (existence of functional benefits), i.e. they enable gaming refresh rates at hundreds of frames per second (FPS) when 30-50 would suffice. Under such conditions, the additional switching costs pertaining to PCIe cannot be justified, since consumers are not likely to acquire performance increases at any cost. In other words, consumers *do not have* to switch to the new architecture; the old one meets their heterogeneous thresholds and firms do continue to bring novel AGP cards to the market. It might be the case that firms in the graphics cards sector are actually attuned to the desires of their customers. Both AMD-ATI and nVidia feature natively hosted user forums, where consumers can obtain information, support, and let out their rants and raves.

The demand context perspective is amenable to other areas of consumer action where similar dynamics take place in technological markets or otherwise. The practice of user generated feedback on commercial products is not new. It has been applied in the evaluation of automobiles, hotel rooms, entertainment media, vintage tube electronics, air-carriers, software applications and platforms, and other areas. The advent of internet-enabled means of mass communication opened up an avenue of inter-user communication, which is unprecedented in scale. Today, more than ever before, consumers are able to communicate with others and create agreement about which commercial products and services are most likely to fulfill their task requirements and at what price. The basic premise underpinning the demand perspective is that demand task requirements are heterogeneous; consumer are fairly well aware of their *diverse* needs and discriminate among the pool of technologies and services that purport to meet these needs.

Implications for the management practice are significant. Managers are often constrained by limited resources in their attempts to bring products and services to markets. At the same time, managers cannot afford to make wrong decisions on too many occasions. Instead of "shooting in the dark", keeping up with consumer desires and needs through natively hosted web-forums or data mining of external forums provides one avenue for not only product/service targeting but also for shaping products/services so as to maximize the fitness between product functionality and actual task-requirement demand. The concept of customer satisfaction surveys is not novel either, but it is often used ad-hoc to suggest areas of improvement. Actually listening to consumers prior to product/service design and manufacture increases the likelihood of product/service offerings and the demand context agreement, thus reducing wasted effort and increasing efficiencies. "Getting it right" and bringing appropriate products to markets sooner offers the potential for disproportionate returns.

Regarding the question of "who selects", this study made a case for the role of consumers (who constitute the demand environment in which technology is evaluated) in the selection of competing technological innovations as well as in the power to influence the longevity of technology designs. The implications of the demand perspective suggest the possibility of progressive, empowering consumer action in the selection and retention of technologies in general.

There are also some important limitations to the demand heterogeneity theory that need to be addressed as well. Adner and Levinthal primarily focus on the functional (technological) value that consumers derive from technology to explain adoption and demand cycles. However, as Shilling (1999) points out, functional utility constitutes only one portion of the combined value of technology (see section 2.1.1). Moreover, she argues, components of value can be actual, perceived, or anticipated, and the latter two can be quite disproportionate compared to the actual combined value. While Adner and Levinthal somewhat address the issue of perceived and anticipated value with their concepts of functional benefits and luxurious bargains, they still focus on the functional utility and neglect other components of combined value (i.e. installed base and complementarities). As indicated in section 1.0 of this paper, technology's stand-alone value of an Apple I-Phone, for example, is not the sole contributing factor in its adoption. Consumers also consider perceived gains in terms of image and identity politics, yet demand heterogeneity theory is completely silent on these issues. After all, technology firms do aim their marketing strategies on associating their products and services with "social benefits" that eclipse immediate functional benefits; and Apple is a true master in this arena.

In addition, demand heterogeneity theory implicitly assumes that consumers are aware of their real functional requirements. That might be true for some savvy technology users who focus on real task requirements to satiate their leisurely ("hard-core gamers") or professional (digital content creators) needs, but not necessarily for other "average" users. On the other hand, it can also be irrelevant whether users are conscious about their primary functional requirements, because any product offering will readily fulfill the task at hand, as indicated by the "fancy cell phone" example in section 3.2 (i.e. any cell phone will fulfill the task of basic mobile communication). Such users might focus on the "extras" instead, but not at any price, as Adner and Levinthal correctly point out.

The question of the type of technology user is thus very important in assessing the boundaries of the demand heterogeneity theory. Consider the example of the professional digital content creator again: There is indication that the central claim of the theory that consumers experience performance increases at stable prices does not apply to these professional users. In particular, workstation graphics cards (as opposed to high-end gaming graphics cards considered in this research) demand significantly higher prices compared to their consumer counterparts. It is known that many workstation AIB's are equivalent to consumer AIB's in terms of hardware, but are rebranded and certified for use with specific professional software (ex: image, video and 3D processing; architectural, engineering, physics and biological/medical sciences applications), require more robust software drivers, and enjoy more extensive technical support. Professional users pay a premium for these added benefits; a high-end consumer cards that costs $400 USD is outright cheap compared to its professional equivalent that costs $3000 USD. This difference in price is on a significant order of magnitude. In other words, the stable price claim cannot be generalized; it depends on firm's branding and customer segmentation strategies. Notice that workstation graphics cards have been excluded from consideration in this research. This decision was deliberate, since the focus was on high-end consumer products. In addition, available data contained significantly fewer workstation cards compared to consumer cards and a conscious decision was made not to mix the two, since they are geared towards different users. It would be interesting to further inquire if professional users also experience increasing performance at stable prices *within* this particular segment.

Similarly, consideration of the type of technology itself is also important for evaluating the boundaries of the theory. Does the theory apply to software products? Apart from high-tech computer peripherals, how does the theory address other technology phenomena such as transportation vehicles, communications devices, or consumer electronics? Consider novel Blue-Ray players compared to DVD players: Is it possible that demand heterogeneity theory might add to our insight into the battle for design dominance between high-definition Blue-Ray and standard definition DVD players? Given that manufacturers still offer DVD players and add chips that "up-convert" standard definition to high-definition content, consumers might choose to "stick" with DVD players for a while, perhaps because they are technologically satisfied and cannot justify the premium charged for Blue-Ray. Such considerations are important to managers, because premature withdrawal from the DVD market will rob them of an important revenue stream. Whether and how these questions can be adequately addressed with the demand perspective alone, or in conjunction with other technology-cycles approaches, certainly offers interesting avenues for further research.

Finally, Adner and Levinthal's assumption that technology needs are fairly constant over time highlights another important limitation of the theory. This is a significant issue that cannot remain unchallenged. The authors of the demand heterogeneity theory based their framework on a mathematical model. Holding technology needs constant certainly helps with the calculus, but it also constitutes an abstract simplification of experienced reality. Throughout this paper, an argument was made that modern technology "over-saturates" consumers' real functional needs. Perhaps in this sense technology needs can be considered constant. For example, if an abstract "technology need" increases over an interval of time, but technology performance also increases at a much higher rate over that same interval, is it fair to argue that the need can be considered constant? A concrete example might help: Moore's Law stipulates that processing speeds double bi-annually; Moore made this observation in 1965. Is it also true that consumer needs have also doubled bi-annually since 1965? Consumer segmentation offers one possible answer: Considering an average consumer who uses the personal computer for word processing, sharing images and clips with family and friends, and reading news on the web, processor speeds necessary for these tasks have been achieved and surpass these functional requirements by a wide margin. Arguably, these task requirements (i.e. needs) can reasonably be deemed constant in this context. On the other hand, a scientist who is interested in neural networks simulation is still left wanting and there is no foreseeable limit to the processing speed that will be required. Consider further the business of marketing as a business of shaping, defining, and creating needs: Average consumers' real needs might be constant, but their perception about their needs is what counts, and that is where the line between needs and wants is blurred. As is usual, the reality is far more complex than any simplified assumptions would suggest. Suffice it to say that Adner and Levinthal's assumption of constant technology needs is a limiting simplification. Therefore, an added area of research that can strengthen the theory or flush out its boundaries revolves around the conditions under which technology needs can reasonably be assumed constant.

In summary, this study set out to test the claims of demand heterogeneity theory regarding the dynamics of demand cycles in the personal computers graphics cards sector. The objective was to test the theory itself against empirical evidence from the evolutionary development of AGP and PCIe data bus architectures. The theory is based on mathematical modeling and remains empirically untested in the management science literature. Conducting such a test, therefore, constitutes the chief contribution of this thesis to the field. An added contribution consist of an attempt to utilize Adner and Levinthal's demand perspective on technology evolution to explain the longevity of the legacy AGP data bus as well as to better understand factors that influence consumer support for technology in the high-tech sector. While the demand heterogeneity theory was shown to be fairly informative in the context of high-tech consumer graphics cards (computer peripherals) segment, questions about the generalizability of the theory remain. The focus on the stand-alone value of technology to the exclusion of the combined value, as well as the assumption of constant technological needs have been identified as limiting factors of the theory in explaining demand cycles. Further issues were raised concerning firms' product and customer segmentation strategies, as well as the type of user and technology itself, all of which impact on technology demand cycles. These issues still provide a fertile ground for further research and evaluation of the demand heterogeneity theory addressed in this thesis.

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Appendix I: Murmann & Frenken's analytical overview of empirical studies on dominant designs (Murmann & Frenken, 2006)

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Authors, Publication Date	Abernathy and Utterback (1978)			Rosenbloom and Cusumano (1987)	Cusumano, Mylonadis, and Rosenbloom (1992)	Anderson and Tushman (1990)			
Topic of Paper	Trade-offs between process (productivity) and product innovation			Technical pioneering and competitive advantage	Strategies for creating dominant designs	Dominant designs / competence-enhancing and competence-destroying innovations			
						Technology 1	Technology 2	Technology 3	Technology 4
Level of Analysis	Entire system	Subsystem	Subsystem	Entire system / subsystem	Entire system/ subsystem	Subsystems	Subsystems	Entire system	Entire system
Product Description	Automobile	Automobile engine	Configuration of parts of internal combustion engines	Video cassette recorders, recording heads	Video cassette recorders	Cement kiln and control unit of kiln	Central processing unit and memory	Container glass machine	Flat glass machine
Nature of Technology	Stand-alone product	Component of system	Collection of components	Product with network externalities, component in system	Product with network externalities	Component of system	Component of system	Stand-alone product	Stand-alone product
Technological Context	Transportation infrastructure, gas stations	Automobile	Internal combustion engine	Home electronics	Network of video stores	Cement production system	Minicomputer systems	Container glass production system	Flat glass production system
Technology Measure					Compatible/non-compatible designs	Capacity of largest kiln	CPU speed	Capacity of fastest machine	Capacity of fastest machine
Market Share Measure	Percent of Total Passenger Cars			Frequency of one-head versus two-head designs	Annual production and cumulative sales by format	New kiln installations	Minicomputer sales by model	New container glass machines	New flat glass machines
Level of Standard	Entire system	Component	Configuration of components	Reading and recording subsystem	Video tape format	Subsystems	Particular architectural feature	Entire system	Entire systems
Description of Standard	Ford Model T chassis (everything except body)	Internal combustion engine	V-8 engine	2-headed rotating scanner	VHS standard	Kiln length/ architecture of heating system	16-bit machine and core memory, 16-bit mos memory	Particular machine name	Particular machine name
DD (Yes, No)	Yes (1908)	Yes (Around1902)	Yes (1930s)	Yes	Yes	4 out of 5 cases	2 out of 3 cases	4 out of 4 cases	2 out 4 cases
Mechanism Creating DD	Cost reduction		Invention of automated production processes		Forming alliance with competing producers				
Critical Dimensions of Success	Price, reliability	Emerging as the better technology	Superior technology	Ability to scale down machine and tape, reduction in price to penetrate mass market	Availability of many prerecorded movies, manufacturing ability, network externalities	Capacity (energy costs)	Speed	Capacity	Capacity
Difference from Earlier or Alternative Designs	Synthesis of independently introduced features into one design	Earlier design approaches included steam or electric mechanisms	More cylinders (earlier models had 2, 4, or 6 cylinders) arranged in different ways	Earlier designs had only one head; sometimes head was fixed	Smaller tape, smaller machine, longer recording hours, cheaper price				

Authors, Publication Date	Utterback and Suarez (1993) and Suarez and Utterback (1995)							
Topic of Paper	Firm entry and exit patterns before and after dominant design							
	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5	Technology 6	Technology 7	Technology 8
Level of Analysis	Entire system	Entire system	Entire system	Subsystem	Subsystems	Subsystem	Entire system	Entire systems
Product Description	Typewriters	Automobiles	TV sets	TV tubes	Transistors	Integrated circuit	Electronic calculator	Super-computer
Nature of Technology	Stand-alone product	Stand-alone product	Component of system	Component of system	Multipurpose component of system	Multipurpose component of system	Stand-alone product	Stand-alone product
Technological Context	Office equipment	Infrastructure, network of gas stations	TV system	TV screens	Various electronic systems	Various electronic systems	Calculating machine	
Technology Measure								
Market Share Measure								
Level of Standard	Entire system	Subsystem	Subsystem	System	Production process systems		System architecture	System architecture
Description of Standard	Underwood Model 5, Hess innovations	All-steel, closed body automobile	21-inch screen, RCA technical standards	All-glass, 21-inch tube	Planar process		Calculator on a chip	
DD (Yes, No)	Yes	Yes	Yes	Yes	Yes	No	Yes	No
Mechanism Creating DD								
Critical Dimensions of Success	Production costs and ease of use				Manufacturing cost and quality		Cost	Cost and speed
Difference from Earlier or Alternative Designs	Incorporates collection of innovations previously available only individually						Reduction of complexity, different knowledge base	

Authors, Publication Date	Henderson and Clark (1990)	Henderson (1995)	Rosenkopf and Tushman (1993)	Van de Ven and Garud (1993)	Khazam and Mowery (1994)	Rosenbloom and Christensen (1994)	Christensen, Suárez, and Utterback (1998)
Topic of Paper	Failure of established firms	Failure of technology life-cycle concept as a forecasting tool	Co-evolution of technology and organization	Co-evolution of technical and institutional events at micro level	Strategies for creating dominant designs	Failure of incumbents to pioneer technology that serves new users and later captures markets of old users	How time of entry in industry life cycle affects failure rates; market vs. technological risks; only architecturally dominant designs have competitive implications
Level of Analysis	Entire system	Entire system	Subsystem	Entire system	Subsystem	Subsystem	Subsystem
Product Description	Photolithographic aligners	Photolithographic aligners	Radio transmitters	Cochlear implants (hearing aids)	Chip architecture	Hard disc drives	Hard disc drives
Nature of Technology	Stand-alone product in larger production system	Stand-alone product in larger production system	Component of system	Stand-alone product	Component of system	Component of system	Component of system
Technological Context	Manufacturing of integrated circuits	Manufacturing of integrated circuits	Radio system	"Human ear"	Workstation computer systems	Computer systems	Computer systems
Technology Measure		Minimum feature size of smallest pattern element it can transfer; throughput; failure rate				Diameter of disc, capacity, area density, access time	Diameter of disc, speed of pancake motor, intelligence of controller
Market Share Measure	Sales revenue by product, R&D cost per development project					Value of shipment of design type by year, cumulative shipment by design	Percentage of models in a given year that incorporate five DD characteristics (see below)
Level of Standard		System architecture (operational principle)	Architecture of subsystem	Architecture of system	Overall chip architecture	Architecture of subsystem	Architecture of subsystem, individual subsystem components
Description of Standard		Optical lithography (using reflective or refractive lenses)	Vacuum tube transmitters	Multichannel design	Sun's Spark chip	IBM Winchester drives (14-, 8-, 5.25-, 3.5-, 2.5-inch)	Winchester architecture, pancake motor at spindle base, voice coil accentuator motor, rotary actuators, intelligent drive electronics
DD (Yes, No)	Not explicit	Yes and No (author uses the term but does not use it as analytical tool)	Yes	Yes	Yes	Yes	Yes
Mechanism Creating DD		User needs, innovations in components, and key complementary technologies	Market selection and government involvement	Agreement by various institutional actors, market selection	Open system strategy	Designs explored for new users later on turn out to be also superior for old users	Better architecture becomes apparent to designers and later adopted by all users
Critical Dimensions of Success	Precision, throughput, failure rate	Investment decisions by firms in particular technology, unexpected improvement in component and complementary technologies	Speech transmission, level of fidelity	Speech discrimination	Speed of processor, development costs, network externalities	Storage capacity, size of disc, cost, reliability	Recording density, storage capacity, size of disc, cost, reliability
Difference from Earlier or Alternative Designs	Reconfiguration of linkages	Reconfiguration of linkages, alternative designs: x-ray aligners and electrobeam aligners that use different wave lengths	Continuous instead of discontinuous wave transmission	Multiple electrodes instead of single one	Removes infrequently used instructions to reduce complexity	Switch from removable disc packs to fixed discs (Winchester drive), then successive changes in disc diameter	Switch from removable disc packs to fixed discs, drive motor relocated, control subsystem added for much better system performance

Authors, Publication Date	Baum et al. (1995)	Iansiti and Khana (1995)	Sanderson and Uzumeri (1995)	Miller et al. (1995)	Wade (1995)	Islas (1999)
Topic of Paper	Dominant designs and firm foundings and deaths	Success of product development processes	Competitive strength based on product families created by changing interface only	Innovation in low-volume systems	Evolution of technical communities and bandwagons creating dominant designs	Evolution of competing technologies for power generation, replacing earlier design trajectory with new one
Level of Analysis	Entire system	Entire system and subsystems	Collection of systems	Entire system and subsystems	Subsystem	Subsystem
Product Description	Facsimile machines	Central processing unit of mainframe computers	Walkman	Flight simulators	Microprocessors	Gas turbine
Nature of Technology	Network-dependent product	Component system	Stand-alone product	Stand-alone product	Component of systems	Component of systems
Technological Context	Facsimile network	Mainframe computers	Personal electronics	Airplanes	Personal computers and workstations	Electric power system
Technology Measure	Compatible/non-compatible designs	MIPS (million instructions per second)	Existence or absence of product feature			
Market Share Measure			US and Japanese market share of personal stereo equipment by firm		Installed base and new sales (this is not a share measure)	Percentage of newly built plants with gas turbines
Level of Standard	Interface subsystem	System-level architecture	Collection of subsystems	Subsystems	Architecture of subsystem	Architecture of subsystem
Description of Standard	Groups 1, 2, 3, 4 (standards)	IBM 360 mainframe architecture	Sony's three platforms underlying 200 Walkman models	Digital computing; six degrees-of-freedom motion	Intel-based processors	Combined cycle gas turbine
DD (Yes, No)	Yes (by committee)	Yes	Yes	Yes	Yes	Yes
Mechanism Creating DD			Reconfiguration of existing subsystem	Standard-setting bodies	Bandwagons (small events lock-in)	The spreading of natural gas as an source of energy to many places, change in legal environment, rise of environmentalism
Critical Dimensions of Success	Compatibility	Compatibility with existing software, speed	Miniaturization, sound quality, energy consumption	Safety, cost, delivery time	Speed, cost, compatibility	Thermal efficiency, low unit cost, availability of cheap natural gas
Difference from Earlier or Alternative Designs	From incompatible to compatible products	Different subsystem architecture	Improvement of old product features and introduction of new product features	Novel approaches to subsystems	Higher speed and density of circuits	Steam turbine, piston compressors, gas (petrol or diesel) engines

Authors, Publication Date	Frenken, Saviotti, and Trommetter (1999)				Rosenkopf and Nerkar (1999)	Burg and Kenney (2000)	Hagedoorn, Carayannis, and Alexander (2001)	Hatfield, Tegarden, and Echols (2001)
Topic of Paper	Variety and standardization in product classes; dominant designs existing only in product niches				Component coevolution in optical disc technology	Role of venture capitalists and dominant designs in creating a new industry	Formation of technological alliances to overthrow the dominant design	Hedging strategies against dominant designs
	Technology 1	Technology 2	Technology 3	Technology 4				
Level of Analysis	Entire system	Entire system	Entire system	Entire system	Subsystem	Subsystem	Entire system	Entire system
Product Description	Aircraft	Helicopters	Motorcycles	Microcomputers	Optical information storage disk	Local Area Network (LAN)	PC computer	PC computer
Nature of Technology	Stand-alone product	Stand-alone product	Stand-alone product	Multipurpose technology	Component in larger system	Linking technology for large number of computers	Multipurpose technology	Multipurpose technology
Technological Context	Transportation system, airports	Heliports (often private)	Roads, gas stations	Software, Internet, electrical power system	Music stereo and later computers	Personal computing	Personal computing	Personal computing
Technology Measure	Discrete (e.g., engine type, number of engines) and continuous technological characteristics (e.g., engine power, range)	Discrete (e.g., engine type, number of engines) and continuous technological characteristics (e.g., engine power, range)	Discrete (e.g., engine type, number of cylinders) and continuous technological characteristics (e.g., engine power, volume, speed)	Discrete (e.g., processor type, operating system) and continuous technological characteristics (e.g., speed, RAM, hard disc memory)	Number of patents for main components of subsystems and their cross-citations			
Market Share Measure	Relative frequency of particular model in product class	Relative frequency of particular model in product class	Relative frequency of particular model in product class	Relative frequency of particular model in product class	Market share of CD players versus AHD and MD optical discs	Number of firms adopting and developing a particular standard	Percentage of PCs shipped with Wintel technology	Percentage of PCs shipped with a certain microprocessor
Level of Standard Description of Standard	Six discrete dimensions	Five discrete dimensions Two turboshaft engines, one rotor helicopter	Three discrete dimensions	Seven discrete dimensions MS-DOS (later Wintel), hard disc, CD ROM	Subsystems level CD optical disc system, later DVD	Subsystems level Ethernet networking protocol	Subsystems level Wintel PC Platform	Subsystems level Intel micro-processor
DD (Yes, No)	Only temporarily (1933-1942); otherwise increase in variety because the product category over time provides a wider scope of services	Yes (decrease in variety)	Only temporarily (1937-1949); otherwise increase in variety because the product category over time provides a wider scope of services	Yes (decrease in variety)	Yes	Yes (mid-1980s)	Yes	Yes (1983)
Mechanism Creating DD	For all three technologies economies of scale limited to a particular niche: Niche formation leads to DD because successful firms scale their design to dominate the niche			Network externalities associated with compatible designs	1. Coalitions of producers and network externalities 2. Negotiation among all firms	Open standard, early backing of large incumbent firm (DEC), slowness of IBM to develop alternative technology, bandwagon of producers joining standard, attracting U.S. venture capital, network externalities	Network externalities	
Critical Dimensions of Success	Limiting competition in product characteristics space	Limiting competition in product characteristics space	Limiting competition in product characteristics space	Compatibility, price	Fidelity of data and sound reproduction, storage capacity, compatibility	Low cost, reliability, transmission speed, great improvement potential, scalability	Large installed base, backward compatibility with DOS, software availability	
Difference from Earlier or Alternative Designs		Turboshaft engine instead of alternative engines, one rotor instead of two, two engines instead of one		Earlier designs had many different operating systems and did not include CD-ROM, color screen, and hard drives	Earlier designs were analog and not digital; competing with CD technology were AHD and MD	Ethernet (as well as the second mover IBM's Token Ring technology) was a non-proprietary open standard, in contrast to DECnet, ARCnet, DOMAIN, Znet, Corvus, Sytek	OS/2, Mac, Osborne, Tandy, Atari, Commodore	

Appendix II: Price, release date and performance indicators distributions of products in the 'GPUReview' data set

The price distribution of cards in the GPUReview data set includes 120 cards only, since 104 price data points are missing. Accurate MSRP data on such a wide range of graphics cards is difficult to obtain and even more challenging to compile. Nevertheless, GPUReview.com offers the most comprehensive database in terms of pricing and manufacturer release dates that could be obtained for this study. Available data for the selected graphics cards segment indicates that the manufacturer's suggested retail price (MSRP) distribution is skewed towards the lower end with the mode of $199 USD being lower than the mean of $320 USD (Figure 16,Table 24).

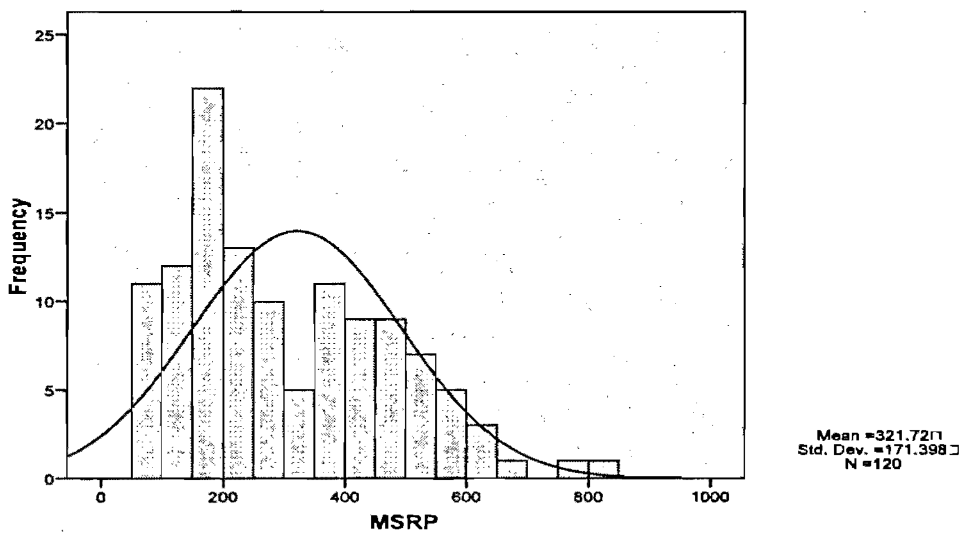

Figure 16: Distribution of MSRP (in USD), AGP and PCIe, 2000-2008, gpuReviewFiltered.sav (GPUReview, 2008)

Table 24 with descriptive statistics of MSRP is given next and is relevant for the discussion of how the concept of Stable Price was constructed.

MSRP

N	Valid	120
	Missing	104
Mean		321.72
Median		299.00
Mode		199
Std. Deviation		171.398
Minimum		55
Maximum		829

Table 24: Descriptive Statistics for MSRP (in USD), AGP and PCIe, 2000-2008, gpuReviewFiltered.sav (GPUReview, 2008)

Figure 17 illustrates the distribution of Release Dates for the cards in this sample set. Most of the 171 cards have been released between late 2004 and late 2008.

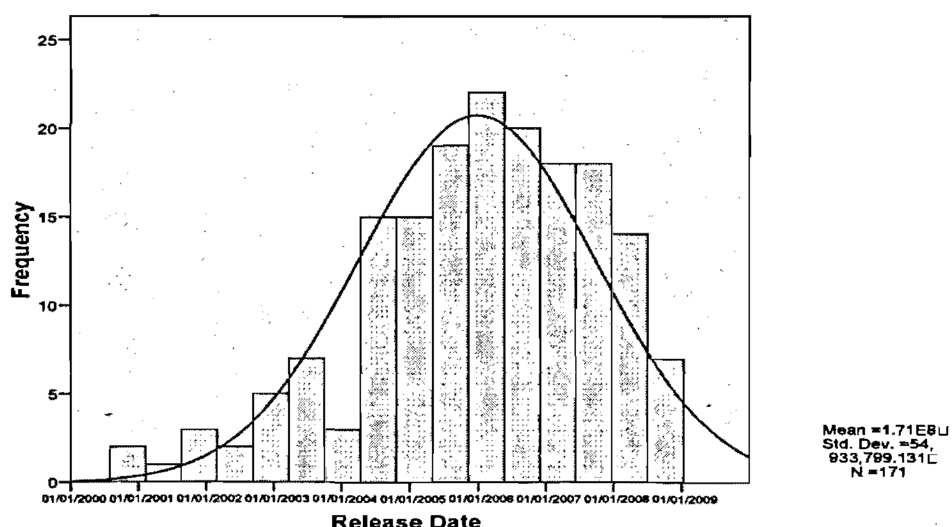

Figure 17: Distribution of Release Date, AGP and PCIe, 2000-2008, gpuReviewFiltered.sav (GPUReview, 2008)

Figure 18 illustrates the distribution of the Core Clock for the cards in this sample set. 224 cards include this data point. The mean core clock speed is 465MHz.

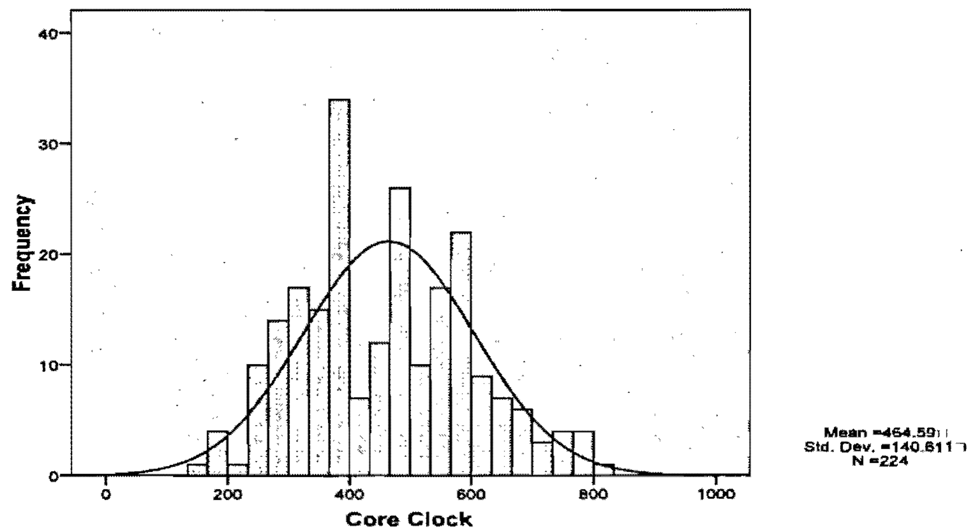

Figure 18: Distribution of Core Clock (in MHz), AGP and PCIe, 2000-2008, gpuReviewFiltered.sav (GPUReview, 2008)

Figure 19 illustrates the distribution of the Memory Clock for the cards in this sample set. 224 cards include this data point. The mean memory clock speed is 506MHz.

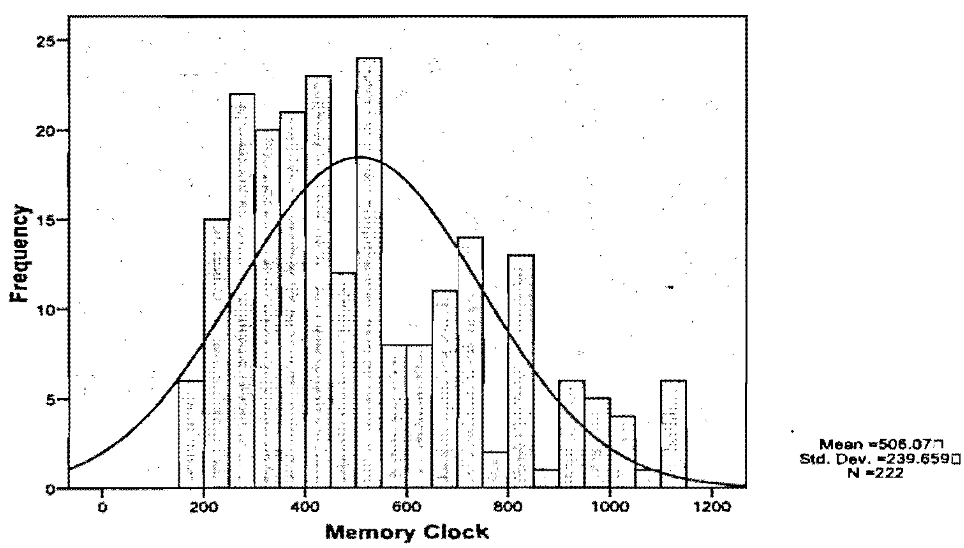

Figure 19: Distribution of Memory Clock (in MHz), AGP and PCIe, 2000-2008, gpuReviewFiltered.sav (GPUReview, 2008)