HEDONIC APPROACHES TO MEASURING PRICE AND QUALITY CHANGE IN PERSONAL COMPUTER SYSTEMS

by

PAUL CHWELOS

B.Sc. Economics, The University of Victoria, 1993

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE STUDIES

(Commerce and Business Administration)

THE UNIVERSITY OF BRITISH COLUMBIA

December 1999

0-612-48622-2

ABSTRACT

Although computers have long been studied in terms of their changing price/performance ratio, the issue of accounting for performance in computer systems has not been adequately addressed. This paper addresses the topic in three ways. First, a survey of IS Managers and business "power-users" of personal computers was conducted to empirically determine the attributes of computer systems that provide value to users; these results guide subsequent choices regarding the operationalisation of user value. Second, an index of system performance was developed from published performance benchmarks and used as a direct measure of performance in the hedonic function. Third, a set of technical proxies was shown to adequately reproduce the performance index derived above, and was used in an alternate specification of the hedonic function. Using data on IBM-PC compatible laptop and desktop systems, price indexes were constructed using both approaches to performance measurement. The results demonstrated that both approaches yielded good explanatory power and nearly identical estimates of the rate of quality adjusted price change in PC systems. Thus, the set of technical proxies could be used to operationalise performance in a larger data set for which direct performance measures are unavailable.

For the 1990s, laptop PCs were found to have decreased in quality adjusted price at an average of 39% per year while the corresponding figure for desktop PCs was 35% per year.

List of Tables

List of Figures

Acknowledgement

I would like to thank all of the "chaps" at UBC: Michael Brydon, Andrew Gemino, and Errol Smythe. These lads were quintessential colleagues, and their intelligence, wit, and good humour made my experience in the doctoral program both more edifying and more enjoyable than it otherwise would have been.

The members of my supervisory committee have provided valuable insight and support that not only improved the dissertation, but also contributed to my development as an academic. For that, I thank you all. I would especially like to thank my supervisor, Al Dexter, who has truly mentored me throughout the program. Your guidance, support, and good nature were invaluable.

Chapter 1: Introduction

If the auto industry had done what the computer industry had done in the last 30 years, a Rolls-Royce would cost $2.50 and get 2,000,000 miles to the gallon.

Forbes, December 22, 1980, p. 24, attributed to *Computerworld* magazine

Computers have long been a topic of investigation in terms of their price/performance ratio. Computer scientists and economists began performing hedonic analyses thirty years ago, and the topic remains of interest because of the ongoing innovation in information technology. This chapter reviews the efforts toward constructing price indexes for several different classes of computing hardware, providing a tour of the "best practice" to date rather than a comprehensive survey.

Computer Price Indexes

Computer price indexes are of intrinsic interest because they answer the question "How quickly are computers coming down in price?" This seemingly simple question requires a sophisticated approach, however. Simplistic methods for measuring price change that do not adequately capture the on-going and rapid quality improvements in computer technology will significantly understate the true rate of price decline. Techniques such a comparing the arithmetic mean of computer prices over time or using the matched-model technique frequently understate the rate of price decline by 10% or more per year. The considerably more sophisticated method of hedonic analysis is required to adequately account for quality change in computers.

A computer price index can be used for two purposes: to deflate nominal expenditures into constant dollars, or to trace out the technological frontier over time. As long as the computer market is in equilibrium, the two measures will be equivalent. However, evidence suggests that due to the rapid technological change, the computer market may rarely be in equilibrium (Dulberger, 1989; Fisher, McGowan, and Greenwood, 1983). Thus, the two purposes are likely to arrive at different indexes, so it is important to be clear about which type of index is being constructed as this will affect choices around data selection and index computation.

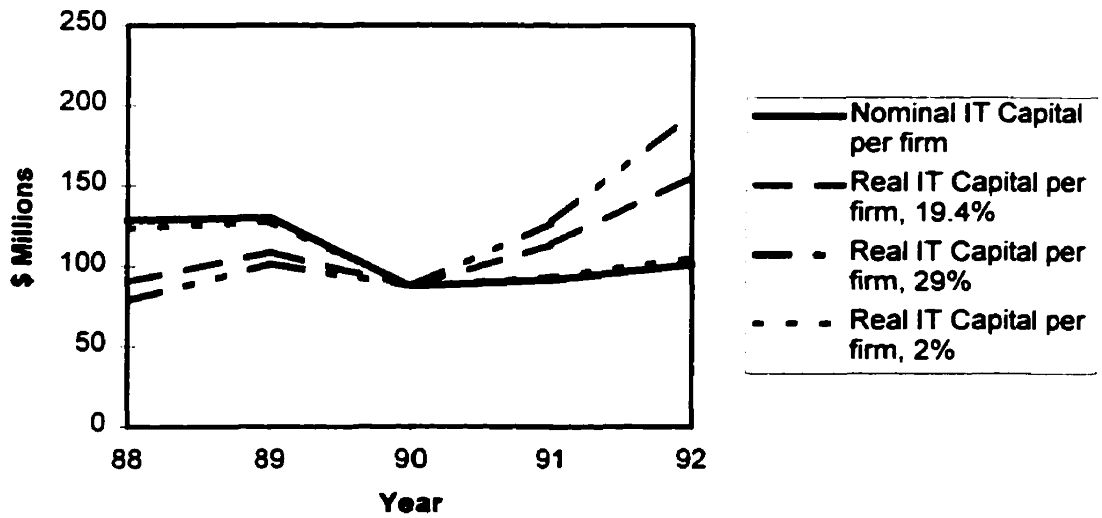
Aside from their intrinsic interest, computer price indexes are critical to a number of types of econometric analysis. On the output side of the economy, a producer price index (PPI) is used to deflate the output of the computer industry to constant dollars. On the input side of the economy, a input-cost index (ICI) is used to deflate investment in computer technology to constant dollars.[1]

---

[1] As discussed in Chapter 3, a PPI and an ICI require different approaches in specifying the hedonic function. To measure quality change from a producer's point of view, the PPI requires a resource-cost

On the output side, there is little doubt that computers have contributed to economic and productivity growth. However, as a input to production the issue of the impact of the computer has not been resolved. (See Appendix 1 for a discussion of the information technology "productivity paradox.") For the accurate analysis of the contribution of factor X to the production of firm Y, two necessary conditions exist: (i) accurate measurement of all inputs (and especially of factor X) to firm Y; and (ii) accurate measurement of the output of firm Y.[2] As noted in Appendix 1, arriving at accurate measures of both input and output has been difficult when computers are the input in question. Computers are most heavily used by the service sector of the economy, the output of which is difficult to measure in constant-quality terms (Baily and Gordon, 1988; Gordon, 1996). As the volume of literature devoted to the topic attests, the measurement of computers as an input to production is also a challenging topic.

Figure 1: Effects of Price Indexes on Real IT Capital



In order to turn time series data on nominal investment (or nominal capital stock) into estimates of the "real" capital stock of IT, an ICI must be applied. Because of the rapid rate of quality improvement in the computer industry, the large magnitude of the ICI for computers makes it play a significant role in any analysis that spans more than a few years. For example, the effect of the computer price index on the estimated "real" IT capital stock for firms in the IDG data set is depicted in Figure 1 above.

---

focus; that is, changes in quality are defined by changes in resource costs. For an ICI, the basis for defining quality is user-value.

[2] In order to estimate a production function, measures of other inputs will also be necessary. At minimum, measures of capital (K) and labour (L) are regressed on value-added.

In all cases, the base year for the application of the price index is 1990. The 19.4% value was derived from a price index constructed for mainframes (Gordon, 1990).[3] The 29% value is an estimated price index for microcomputers (Berndt, Griliches, and Rappaport, 1995). The 2% value is chosen to represent the behaviour of an ICI for more typical capital. As can be seen from the graph, the computer price index has a significant impact on the measurement of the IT capital stock in real terms. Because the level of the ICI does not affect the measures of the output of firms, changes in the measures of the inputs must affect the results of the production function estimation. The resulting changes in the estimates depend on the form chosen for the production function. The results most affected, of course, will be the estimated returns to investment in computers. Thus, the computer ICI plays a central role in evaluating the productive impacts of information technology. Recent work has empirically demonstrated that the choice of price index applied to IT capital critically affects the estimated returns to IT investment (Barua and Lee, 1997).

In addition to its importance in production function estimation, an ICI is also central to empirical work that directly estimates consumer surplus arising from the price declines in computer technology (e.g., Bresnahan, 1986; Brynjolfsson, 1996). Given data on nominal spending on computers, the estimated increases in consumer welfare are entirely driven by the ICI, so the accuracy of the measure of quality-adjusted price decline is obviously critical. Thus, in addition to being inherently meaningful, an ICI for computers is fundamental to econometric work that needs measures of computers as an input to production.

Prior Work on Computer Price Indexes

A recent survey of empirical work on computer price indexes is extremely thorough and detailed (Triplett, 1989). As well as reviewing twenty-five studies, the author does some work toward constructing a price index for "computer systems," defined as a processor (mainframe or minicomputer) plus peripherals (printer, disk drives, and terminals). This paper also makes a significant contribution to our understanding of the methodology of using a hedonic function to construct a price index for the outputs of the computer industry. By taking a weighted average of the indexes produced by the studies judged to be of the most sound methodology, a "best practice" price index for computer processors is constructed for the period 1953-1972.[4]

Mainframes and Mini-Computers

Mainframe processors, and later minicomputer processors, have received the most research attention. The earliest hedonic work was pioneered by Gregory Chow and Frank Knight.[5] Chow uses three independent variables: quantity of RAM, time to perform a multiplication instruction, and memory access time (Chow, 1967). Knight uses his own specification for computing "power" as well as a measure of computer reliability,

---

[3] This index was constructed using solely mainframes as the sample, and the data ends in 1984. Although clearly not ideal for the IDG data set, which encompasses more than mainframes and does not begin until 1988, this index was the best available. The 19.4% value is simply assumed to hold for 1988-1992.

[4] For the period 1972-1984, Triplett favours the index of Dulberger (1989), discussed below.

[5] Discussion of this work is drawn from Triplett (1989).

defined as monthly seconds of "up time" per dollar of monthly rental (Knight, 1966). Knight's specification of power is:

$$C = \frac{10^{12}(M(L-7)Wk)^a}{t_1 + t_2} \tag{1}$$

where,

M = memory size (in words)

L = word length (in bits)

W = "word factor" (dummy variable for memory type)

k = scaling constant

t_1 = time (in microseconds) to perform one million operations

t_2 = I/O or other idle time (in microseconds) for one million operations

$a = 0.05$ for "scientific," 0.33 for "commercial"

While Knight's power specification has been criticised for the apparently arbitrary nature of some of its parameters (as well as its overall form), it is more technologically astute than many later studies. Knight's index incorporates a measure of system "overhead," the idle time a system wastes waiting for input-output operations or performing other, low-level operating system tasks that do not contribute to the performance of calculations. Knight's computing power index measures the potential of a box to perform useful computations. This measure, combined with his reliability measure, provides one of the best assessments of user-value provided in any econometric study of computers.

A joint effort between IBM and the BEA led to the adoption of a hedonic price index for computers, covering the period 1972 to 1984 (Cole, Chen, Barquin-Stolleman, Dulberger, Helvacian, and Hodge, 1986; Triplett, 1986; Cartwright, 1986). For computer processors, the average annual rate of price change (AARPC) was roughly -19.2% over this period. This work was reapplied to the period 1983 to 1988 (Cartwright and Smith, 1988; Dulberger, 1989). For computer processors, three independent variables were used to account for the "quality" of systems: the quantity of random access memory (RAM), a measure of processor speed (operationalised as MIPS), and a set of dummy variables that capture generations of technology. The data set is restricted to IBM models and "plug compatible" machines, and thus possesses a potential bias in that it may not accurately represent the entire market. This sample limitation does ensure, however, that the MIPS ratings are truly comparable across all machines, thus enabling an accurate accounting of quality change. The researchers estimate price indexes using four index-number formulas and do a reasonable amount of testing for accurate specification of the hedonic function.[6]

One detractor from these findings is Robert Gordon (Gordon, 1989a), who takes issue with the selection of data and the chosen methods. The resulting debate (Cole et al., 1989; Gordon, 1989b) has illuminated several important methodological points. First, it

[6] The approaches to measuring the speed of computers, as well as the methodology of computing price indexes will be discussed more thoroughly in Chapter 3.

is important to define the purpose of the price index: tracing the technological frontier or deflating purchases of computers. Second, and according to that purpose, the data must be chosen appropriately: for an estimation of the technological frontier, data on "new" models only may be appropriate, while for deflating purchases, as wide a data set as possible should be used.[7] Third, a keen understanding of the generations of technology in the computer market is required to make intelligent choices about the specification of hedonic analyses. Fourth, the choices made about data must be applied consistently across the entire time frame to avoid "double-counting" or otherwise biasing the estimated index. For example, Gordon claims that Triplett's "best practice" index makes a shift in data sources from new models only to sources that include older models after 1965, and hence may double-count the price decreases due to the introduction of the IBM 360 family. What is made most clear by this debate is that consistency in sources of data and application of methods is crucial to producing a valid index.

Recently, the approach of Cole et al. has been reapplied to the mainframe market for the years 1984-94 (Caudill and Gropper, 1997). Using data from the publication *Computer Price Watch* (new models only), a price index is constructed using only a single measure, a "relative performance index," to account for quality change. This approach walks the line between parsimony and unsophistication: while a single attribute certainly cannot capture all aspects of the "quality" of a mainframe, the empirical measures of model fit are very high, indicating that the "relative performance index" is doing an excellent job of accounting for observed prices in the marketplace.[8] Unfortunately the nature of this measure is not made explicit by the authors, leaving the reader to conclude that it is likely a measure of MIPS. The authors use four methods to calculate their price index, producing estimates that range from 16.6% to 19.7% average annual decline in quality-adjusted prices. These estimates are in the approximate range of those produced by Cole et al. (19.2%) for the 1972-84 period.

Peripherals

A few studies have addressed price change in the equipment that is peripheral to a mainframe or microcomputer system. This section will not discuss these thoroughly, for two reasons: (i) the measurement of quality change for peripherals is slightly more straightforward than for computer processors (or at least less contentious); and (ii) with the shift toward microcomputers, the measurement of "peripherals" becomes irrelevant as disk-drives and monitors are bundled as part of stand-alone systems.

Cole et al. (1986) also constructs indexes for three classes of peripherals: disk drives, printers, and terminals. For their 1972-1984 sample, the AARPC's are -14.4%, -15.9%, and -7.9%, respectively. Flamm (1987) examines disk drives, tape drives, printers, and card reader/punches for the period 1957-1978, finding annual AARPC's for each of these classes of peripherals to be -24.6%, -28.7%, -12.4, and -10.9%, respectively.

---

[7] Although Cole, Dulberger, and Triplett (1990) argue that some models on the technological frontier may not appear to be "new" models, and that not all "new" models will be on the technological frontier.

[8] The R^2 for the pooled approach is 0.942, and for the adjacent years approach, R^2 ranges from 0.908 to 0.982.

Although Flamm uses only a single attribute for each class of peripheral, his results accord quite closely with those of Cole et al. (1986), which gives confidence in them.[9]

While the price behaviour of peripherals is of some intrinsic interest, peripherals are only sub-components of complete computing systems. Thus, the more important, and considerably more complicated, question addresses the price behaviour of computer systems over time.

Systems

Narrowly defined, a computer system is the collection of a processor, secondary storage such as disk and/or tape drives, and input-output equipment such as printers and terminals; Triplett (1989) defines it as "an optimal combination of computer equipment—processors and peripherals—for a specific employment."[10] A broader definition would incorporate all of the elements that are inputs to an organisation's computing centre: computer hardware, operating system, application software, infrastructure, labour, electricity, and so on. The broader the definition of a computer system, the more accurately it may reflect the cost of computing as an input to production within an organisation.

With increasing breadth, however, comes a host of measurement problems: configurations will vary dramatically across organisations; data collection problems will increase several fold as data for not only hardware, but also other inputs must be collected; and measuring the performance of entire systems becomes more complex. This sort of data may be impossible to collect retrospectively, so constructing a price index over a significant length of time becomes intractable. Thus, the most feasible definition of a computer system that accurately reflects what consumers actually purchase is "the combination of computer equipment and operating system."

Very little work has been done to construct a price index for an entire computer system, likely due to the data problems mentioned above. Triplett (1989) makes the assumptions necessary to treat a computer system as a collection of components. Specifically, he assumes that the output of the computer centre is separable on the pieces of computer equipment; this assumption is equivalent to stating that there are no interactions between system components. Triplett (1989) constructs a "Time-series Generalised Fisher Ideal" index (TGFI) for computer systems, using as weights data on the sales of computer processors and peripherals.

There are a number of reasons to dispute the assumption that the output of the computer centre is separable on the pieces of computer equipment. Cole et al. (1986) state:

> Although working at the box level [i.e., components, not systems] reduces many of the problems of measurement, it is important to recognise that both the hardware and software of a computing system embody attributes—such as ease of installation, reliability, and ease of use—that

[9] This close correspondence is achieved even though Triplett makes the questionable decision of equating Flamm's index for card readers/punches to the Cole et al. index for terminals.

[10] Triplet (1989), p. 192

> are not easily measured. Working at the box level is likely to understate the improvements that have occurred in computing systems over the years.[11]

Similarly, Gordon (1989) remarks:

> However, as Franklin M. Fisher has pointed out to me in correspondence, the improvement in computer performance involves the way in which processors interface with peripherals and with operating systems. While Fisher does not think that it is possible to handle this problem with available methods and data, he suggests that the failure of this and other studies to quantify the benefits of improved interaction between processors and peripherals causes the true rate of improvement in the performance of computer systems to be understated.[12]

Finally, Dulberger (1989) notes:

> The second consideration is a practical one concerning the tractability of measurement of performance characteristics and the feasibility of measuring performance with the hedonic technique. At the component level, performance characteristics, of value to both producer and purchaser, are based on each component's role in the system. System performance, however, though driven to a large extent by the performance of individual hardware components, has the added dimension of component interactions (and nonhardware elements such as system and application software). Information-processing systems get the work done through a network of component queues. Research, thus far, indicates that such analysis requires a more complicated technique than the hedonic one.[13]

Thus, there appears to be agreement among researchers that the performance of a computer system is not simply an aggregation of the performance of the components; rather, gradual tuning of the interaction between components has apparently resulted in significant performance improvements beyond the individual improvements in each of the components. Thus, measuring just the speed of components likely understates the true rate of technological improvement, thereby biasing the price index for computer systems. The issue of assessing the performance of a computer system will be discussed more fully in Chapters 3 and 4.

Microcomputers

Microcomputers, being the most recently developed class of computers, have received the least attention in terms of the construction of hedonic price indexes. To date, three studies stand out as the most rigorous (Berndt and Griliches, 1990; Nelson et al., 1994; Berndt et al., 1995).

---

[11] Cole et al. (1986), p. 41

[12] Gordon (1989a), p. 91

[13] Dulberger (1989), p. 39-40

There are two major differences between the two Berndt and Griliches papers: the time period covered (1976-1988 versus 1989-1992) and the data sources. Berndt and Griliches (1990) pulls the data on computer prices and attributes from advertisements in Byte, PC Magazine, PC World, and the New York Times; while Berndt et al. (1995) uses data from Datapro Information Services Group. The Datapro data provides more information on technical specifications of the computers, but do not provide any performance measures. While the extra technical information allows the authors to specify a more elaborate hedonic function, the shift in data has the major drawback of making the two data sets (1982-88 and 1988-92) non-comparable, so an index covering the period 1982-92 cannot be constructed.

Both of these papers make contributions to our understanding of specifying hedonic functions in which the identity Time = Vintage + Age holds. Two versions of a specification test are developed, in essence stating that that, in a properly specified hedonic function, we can reject the hypothesis that the parameters on vintage variables are non-zero. Thus, unmeasured price change should be unrelated to the vintage of the model; this result requires that the hedonic function is capturing all sources of user value (or that the unmeasured sources of user value are uncorrelated to vintage).

The empirical results are quite similar for the two papers: over the 1982-88 period, they find that quality-adjusted prices for microcomputers decline at about 28% per year; for the 1988-1992 period, the figure is 30% per year.

While these papers are sound in terms of their theoretical contribution to methodology as well as their empirical construction of price indexes, they have been critiqued in terms of their specification of the hedonic function (see Chapter 2). In the first paper, the authors account for quality change in microcomputers using the speed of the machine (operationalised as the word-length and clock speed of the CPU, as well as the quantity of RAM), the presence of a monitor, the size of the hard drive, and the brand of the system. In the second paper, the authors take a much more detailed approach to measuring quality. In addition to proxies for performance (again, CPU clock speed and word length), the hedonic function includes RAM, the maximum potential RAM, hard disk capacity, the weight of the system, the volume of the case, as well as a number of terms composed of both the squares of these values and of interactions between these values.

Concurrently, a somewhat more detailed approach to accounting for quality change in PCs was undertaken (Nelson et al., 1994). In this paper, the authors restrict their analysis to IBM-PC compatible machines, allowing a cleaner specification of the hedonic function. The authors display good knowledge of PC systems, which allows them to construct a sensible hedonic function. For example, by using dummy variables, the authors completely specify all generations of Intel CPUs for the 1984-1991 time period, from the 8088 to the 80486. The key strength of this paper is clearly the specification of the hedonic function, as the econometric issues are not as well addressed as in the two previously discussed microcomputer papers. However, even in this paper, the issue of performance measurement has not been fully resolved, as the authors mistakenly treat a MHz of clock speed as a homogenous good across generations of CPUs (see Chapter 2).

Using a hedonic function to account for quality change requires a thorough understanding of the technology in order to assess the sources of user value. While the authors of the three studies discussed above are excellent econometricians, they did not appear to understand the business value of the technology well enough to specify the hedonic function adequately. Chapter 2 contains a detailed critique of these studies, and ultimately recommends three classes of modifications to the hedonic function: (i) the elimination of attributes that do not measure user value; (ii) the inclusion of omitted attributes that are important sources of user value, and (iii) the exploration of issues around the choice of functional form for the hedonic function.

The hedonic approach has also been applied to examining the prices that prevailed in the workstation market in 1989 (Rao and Lynch, 1993).[14] Since the authors examine only one year, they obviously do not construct a price index. Two interesting points surface in this study. First, the specification revealed as best by a Box-Cox test is, in this data set, linear. This finding is at odds with earlier work that found the double-log to be the preferred functional form for microcomputers. Second, the study includes a type of synthetic benchmark (MIPS) as a measure of performance or system quality. The resulting hedonic function displays good fit on a variety of metrics, including a high R^2 (0.776). Although the specification is relatively parsimonious, it covers the major determinants of user value in workstations: performance, hard drive space, RAM, drive interface, colour versus monochrome monitor, and the major brands (DEC, Sun, and Hewlett-Packard). This paper provides the only known use of a direct performance measure in an estimated hedonic function for microcomputers, but, as mentioned above, does not construct a price index.

A recent paper has examined the price change in the market for laptop PCs (Baker, 1997). This study uses data from an annual review of laptops published in *PC Magazine,* drawing data from the period 1990-1995. By and large, the author follows the specification for laptops used previously, including terms such as weight, volume, and density as sources of user value. The author makes an interesting choice in modelling performance, however: "In this study, only MHz is included as a variable for processor capability under the assumption that MHz is highly correlated with other characteristics represented by the type of chip." As has been argued above, however, a "MHz" is not a homogeneous attribute, and the "value" of a processor's clock speed cannot be meaningfully discussed without specifying the generation of that processor. In this data set, processors cover four major generations of CPUs (from the 286 to the Pentium), encompassing easily an order-of-magnitude change in computing capability on a per-clock-cycle basis. The assumption that MHz is correlated with the generation of CPU is loosely true, but in any given year, computers with different generations of CPU with similar clock speeds will be available in the market, typically at significantly different prices, *ceteris paribus.* Thus, it should not be seen as surprising when the empirical estimation "unexpectedly" reveals MHz to be statistically insignificant. The author tests the non-linear specification of the hedonic function used in Nelson et al. (1994), and finds the time by MHz interaction term to be significant and positive, again an "unexpected" finding. However, this finding provides further evidence of the importance of considering processor generation when examining processor clock speed; the positive

[14] Workstations are typically considered to be microcomputers that are more powerful than high-end PCs, but there is significant overlap between these two groups. The distinction is sometimes easier to make by operating system (workstations may run some version of the Unix rather than DOS or Windows OS), processor (perhaps non-Intel processor), or application (workstations are used for computationally intensive tasks such as sound or video editing, computer-aided design, or statistical analysis). In 1989, workstations were defined as microcomputers had at least a 32-bit processor, 4 MB of RAM, 1024x768 resolution, at least a 70 MB hard drive, and a network interface card.

coefficient can be interpreted as reflecting the fact that, even accounting for price decreases over the sample period, the sample reflects MHz that are more valuable in later years because they represent more advanced generations of processors.

Complicating Complements

As mentioned in the discussion of computer systems and microcomputers, the issue of accounting for price and quality change in computer hardware is complicated by the complementary relationships between computer hardware and other inputs, such as operating system and applications software, skilled labour, and telecommunications infrastructure. Accounting for quality change in the entire computer input to a firm would require a firm-level definition of computing and telecommunications, with a system-level metric for quality. Aside from presenting a tremendously difficult aggregation problem, this issue would require the construction of separate quality measures and resulting price indexes for each firm or organisation. Thus, this issue has not been meaningfully tackled outside of the treatment that assumes separability between inputs (Triplett, 1989).

One approach measuring and assessing the complementarities between different IT inputs would require separate price indexes for each class of IT inputs. Using these indexes, estimates of real capital stocks of hardware, software, and telecommunications infrastructure could be used as inputs to production function estimation. The nature of the productive complementarities between these inputs could thus be explored empirically. Preliminary work on a price index for data communications networks is underway with the sponsorship of Cisco Systems, Inc. A limited amount of work has examined applications software using hedonic techniques. For example, spreadsheets were found to have declined in price, in quality-adjusted terms, at an average of 15% per year over the period 1986-1991 (Gandal, 1994), or by 16% over the period 1987-1992 (Brynjolfsson and Kemerer, 1996). Likewise, database software in Germany was found to decline in quality adjusted price at about 7-9% per year from 1986 to 1994 (Harhoff and Moch, 1997). While the measurement of price change in computer hardware remains problematic, it is relatively mature compared to the measurement of price changes in other classes of IT inputs, for which measurement is clearly in its infancy.

Summary of Empirical Work

The major focus of empirical studies has been "computer processors," typically taken to be the combination of the central processing unit (CPU) and the main memory (RAM). Due to the on-going miniaturisation of computers, "personal-" or "micro-" computers have come to dominate the market in the 1990s. These small machines are actually entire computer systems in a single box. Thus, the level of analysis has consequently shifted from "processors" to computer systems.

Despite the long history of hedonic analyses on computers, a number of major problems remain to be addressed. Triplett (1989) chastised researchers for lack of thorough testing for the correct specification of the functional form of the hedonic function. He also notes that one class of functional forms that may prevail has not be tested. Recent work on microcomputers has suffered from possible misspecification of the attributes to be included in the hedonic function (i.e., they may not represent sources of user value).

None of the work to date has yet used benchmarks, perhaps the best measure of system performance. In their first paper on microcomputers, Berndt and Griliches (1990) note:

> One item high on our research agenda involves obtaining model-specific performance measures for specific numerical tasks, such as the number of instructions executed per unit of time, and then re-doing our hedonic regressions with such performance measures added as regressors. Moreover, the issues of parameter instability and choice of variables to include in the set of characteristics are also potentially important, and need further examination.[15]

Hence, while the empirical research to date has illuminated many issues and provided useful estimates of the rate of price change in the markets for computers, a number of issues regarding the specification of the hedonic function remain to be resolved.

Dissertation Outline

This dissertation addresses the measurement of IT as an input to production. Specifically, the problem to be addressed is that of measuring quality-adjusted price change in one class IT hardware: IBM-PC compatible microcomputers (PC's) and portables. The principal contribution of this dissertation is the development of two approaches to the construction of personal computer price indexes (PCPI).

The remainder of the dissertation is organised as follows. Chapter 2 critiques the most significant prior work on microcomputer price indexes. Chapter 3 introduces the theory used to account for quality change and describes the Delphi Survey conducted to assist in specifying the methodology. Chapters 4 and 5 compute price indexes for laptop and desktop PCs, respectively. Chapter 6 concludes by discussing the implications and limitations of this work.

Appendix 1 positions the dissertation within the larger context of econometric research aimed at measuring the return on the investment in information technology. Prior research is reviewed, and the candidate explanations for this "productivity paradox" are explored. Regardless of which, if any, explanations are credible, it is clear that better measurement of IT as an input to production will contribute to more accurate measurement of the returns to investment in that input.

Appendix 2 contains the instruments used in the Delphi survey.

---

[15] Berndt and Griliches (1990), p. 35

Chapter 2: Critique of Prior Research on Microcomputers

This chapter discusses three closely related empirical papers that develop estimates of price indexes for microcomputers using hedonic techniques (Berndt and Griliches, 1990; Nelson et al., 1994; Berndt et al., 1995). The two Berndt and Griliches papers are very similar in methodology and approach; the major differences between the two are data sources and time periods: the first uses magazine advertisements for data on microcomputer prices and Byte magazine technical reviews for data on attributes for the period 1982-88 while the second acquires the same data for the 1989-92 period from the market research firm Datapro. The Nelson et al. paper focuses on the period 1984-1991, using data from computer trade publications. The authors' own abstracts provide the most concise summary of the papers:

Berndt and Griliches (1990) abstract:

> In this paper we focus on alternative procedures for calculating and interpreting quality-adjusted price indexes for microcomputers, based on a variety of estimated hedonic price equations. Our data set comprises and unbalanced panel for 1265 model observations from 1982 to 1988, and includes both list and discount prices. We develop and implement empirically a specification test for selecting preferable hedonic price equations, and consider in detail the alternative interpretations of dummy variable coefficients having time and age, vintage and age, and all of the time, age, and vintage dummy variables as regressors.
>
> We then calculate a variety of quality-adjusted price indexes; for the Divisia indexes we employ estimated hedonic price equations to predict prices of unobserved models (pre-entry and post-exit). Although our indexes show a modest amount of variation, we find that on average over the 1982-88 time period in the US, quality-adjusted real prices for microcomputers decline at about 28% per year.

Berndt, Griliches, and Rappaport (1995) abstract:

> In this paper we construct a number of quality-adjusted price indexes for personal computers in the US marketplace over the 1989-92 time period. We generalise earlier work by incorporating simultaneously the time, age, and vintage effects of computer models and then develop a corresponding specification test procedure. When data on new and surviving models are used in the estimation of hedonic price equations, a variety of quality-adjusted price indexes decline at about 30% per year, with a particularly large drop occurring in 1992. We conclude that taking quality changes into account has an enormous impact on the time pattern of price indexes for PC's.

Nelson, Tanguay, and Patterson (1994) abstract:

> This study estimates quality-adjusted price indexes for personal computers. Three separate hedonic models are estimated using data from 1,841 personal computers over the period 1984-1991. In addition to the traditional linear model, a non-linear model is developed and estimated. The non-linear

model is parsimonious in parameters, allows time-varying attribute prices, and can be estimated using a pooled data set. The results indicate that the nominal quality-adjusted prices of mail-order firms declined at an average annual rate of 24.62%; quality-adjusted prices of major manufacturers declined at a slower rate.

Comments on Berndt and Griliches (1990):

The 1990 paper is a sound piece of research that not only derives interesting empirical results (preliminary price indexes for microcomputers), but also contributes to our understanding of the methodology underlying such studies by developing a specification test. This test requires that the estimated parameters on the vintage variables should not be significantly different than zero.

The authors start by noting that price indexes in such a dynamic market (microcomputers) can be used for two purposes: (i) to deflate expenditures into constant dollars, and (ii) to trace movements in the technological frontier, i.e., the price-performance ratio. If the market were always in equilibrium, then the two would be the same, but disequilibrium might exist for a number of reasons: shortages in the supply of new models, quality differences in unobserved characteristics, etc.

The data on microcomputer list prices comes from June issues of Byte, PC Magazine, and PC World; the data on discount prices comes from the Sunday issue of the New York Times; the data on microcomputer technical specifications comes from Byte Magazine technical reviews.

In specifying their hedonic function, the authors use the following continuous variables: the quantity of RAM, measured in kilobytes; the speed of the CPU, measured in MHz; the size of the hard disk HRDDSK, measured in megabytes; the number of floppy drives; and the number of expansion slots on the motherboard. Dummy variables included: PROC16 (16-bit processor); PROC32 (32-bit processor); DBW (monochrome monitor); DCOLOR(colour monitor); DPORT (portable computer); DEXTRA (if the system comes with extra hardware, e.g., printer, modem, or extra monitor); DDISC (if the price is discounted), and a number of dummy variables of the form Dxxx, where "xxx" identifies a manufacturer (e.g., Apple, IBM, Compaq). By the specification of the dummy variables, the default model has an 8-bit processor, does not include a monitor, is not a portable model, is sold at list prices, and is made by IBM.

In specifying a hedonic function, the independent variables included as determinants of the price of the heterogeneous good should reflect at least one of two things: a resource-cost used in production or a source of user-value. As has been pointed out, the appropriate focus for an index that is intended to deflate purchases into constant dollars is that of user-value (Triplett, 1989). Thus, the variables included in a hedonic analysis for microcomputers should reflect sources of user value, or at least be a proxy for them.[16]

While this list of attributes is a very good first-cut at specifying a hedonic function, a number of attributes were not included that may be significant sources of user-value.

[16] Triplett (1986) discusses the dangers of using proxy variables.

Candidates that should at least be tested for significance include: the distinction between "SX" and "DX" 386 processors; the distinction between 8086 and 8088 processors; the presence of a math co-processor (the "387"); the architecture of the motherboard (i.e., ISA versus Microchannel); the bundled operating system (e.g., generations of PC- and MS-DOS, Microsoft Windows, and OS/2); and differentiating between "extra" hardware (e.g., modem, mouse, printer, extra monitor). This list could be considerably extended with additional technical attributes that are legitimate candidates as sources of user value; however, the tension between parsimony and completeness would have to be assessed on an attribute-by-attribute basis.[17]

In recent years, anecdotal evidence suggests that systems using the latest model of PC processor appears to command a premium in terms of the price/performance ratio. For example, shortly after its introduction, a 500 MHz Pentium-II processor sold for C$1280, while the 400MHz version sold for C$540. In performance terms, the a system based on a 500 MHz CPU could be, at most, 25% faster than a system using the 400 MHz CPU, but was priced at 137% more. To capture this effect a "best technology" dummy variable could also be included in the hedonic function. It has previously been demonstrated, for mainframe processors, that accounting for the generation of technology was important to the adequate specification of the hedonic function (Cole et al., 1986; Dulberger, 1989). Ironically, in the mainframe market, the latest technology typically sold for a discount, in price/performance terms, compared to older technology, thus suggesting that the mainframe market dominated by IBM was more competitive than the PC market dominated by Intel.

Thus, there may be room for improvement in the specification of this "classical" hedonic function, in which the independent variables are (technical) attributes of the heterogeneous good. However, there is also room for a revised specification of the hedonic function that attempts to more directly measure the sources of user value.

The technical attributes included as independent variables above are primarily indirect measures of user value. For example, the quantity of RAM in a system does not provide its user with intrinsic utility in the same way that, say, an automatic transmission provides utility to the user of a car. The inclusion of RAM in a hedonic regression is largely justified because increases in RAM, *ceteris paribus*, will improve the performance of a microcomputer system.[18] However, the relationship between system RAM and system performance depends on a number of factors, and has been shown to be non-linear. Likewise, most of the independent variables above represent, at best, indirect sources of user value.[19]

---

[17] A non-exhaustive list of these candidates includes attributes of the monitor (viewing area; maximum resolution and refresh rates; dot pitch; as well as subjective ratings of viewing quality) of the motherboard (number of 8-bit, 16-bit, and 32-bit expansion slots; the manufacturer; the design of the supporting chip sets; and clock speed) and of the extras (manufacturer; appropriate quality measures for printers and modems).

[18] RAM does provide direct utility in its ability to support multitasking in a windowed operating system. This direct benefit or RAM could not be realised before the widespread adoption of a PC operating system that could manage more than one megabyte of RAM and support multitasking. Thus, any direct benefits of RAM are unlikely to accrue prior to the release of Windows 3.0 in 1990.

[19] An exception may be hard disk space (HDDSK), as secondary storage space provides value to users in being able to store more data and applications.

A more direct approach of assessing user-value would be to include measures of system performance.[20] Ultimately, a user derives value from two things when using a microcomputer: the range of tasks she can perform, and the speed at which she can perform them. Measures of the range of tasks are beyond the scope of improvement in the quality of the computer, resulting more from the development of new application-software than from the increase in the speed of a microcomputer. Hence, scope will not be addressed in this paper.[21] The second source of user value, the speed or "power" of the computer has been, along with RAM, a traditional independent variable in hedonic analyses of computer processors (Triplett, 1989).

However, a microcomputer is different from a "computer processor" as it has traditionally been defined: the combination of CPU and RAM. A microcomputer is actually a complete "computer system," consisting of a computer processor, "secondary storage" (a hard drive), and a "terminal" (video card, monitor, and keyboard). Because a microcomputer is a complete computer system, the system-level becomes the only meaningful level of analysis in terms of quality change.

Hedonic analysis has done very little work in addressing computer systems, most likely due to the complex interrelationships between the performance of the components (processor, secondary storage, terminals, and printers) and the performance of the entire system. An analytical treatment of these relationships would require a considerably more detailed treatment than a hedonic function allows (Dulberger, 1989). Thus, the issue of changes in the performance of systems, separate from changes in the performance of components, has received little treatment. This decision has been more justifiable in the past when individual components were the most frequently purchased units, and buyers rarely purchased entire systems as a whole.[22] In this era, there was no clearly identifiable "typical system" or typical configuration for the use of a processor; instead, firms adapted the amount of processing, storage, and input-output capacity to their needs. This lack of a typical system made measuring the quality change of systems both more difficult and less meaningful.

With a microcomputer, however, a system (and only one system) is clearly identifiable—that which is sold. There are two approaches to assessing system performance: (i) analytically modelling the interaction between system components; and (ii) directly measuring system performance on a set of tasks constructed so as to be representative of the interests of the typical user. The former approach, while intrinsically interesting to the designers of such systems, can at best be an approximation to the latter.

The approach of directly measuring the speed of a computer system on a representative set of tasks is known as "benchmarking" or a "benchmark test." The chief drawback to a benchmark test has been its cost (Triplett, 1989). In the past, running a truly

---

[20] Strictly speaking, the speed of the CPU is an intermediate-stage proxy measure (Triplett, 1989) for the speed at which the system performs useful work.

[21] A major redefinition of the scope of tasks that can be accomplished on a microcomputer is due to the increased use of networks to link computers. As the 1990s draw to a close, one of the major sources of value of microcomputers appears to be their use as a communications tool. This issue is most appropriately addressed by a separate index that would address the cost of electronic communication, and is a worthwhile topic for future research.

[22] See Cole, Chen, Barquin-Stolleman, Dulberger, Helvacian, and Hodge (1986), Dulberger (1989), Gordon (1989) and Triplett (1989) for discussions of the component versus system levels of analysis.

representative set of jobs on a mainframe computer could consume significant computing resources. With the increases in speed of computers, however, the cost of the tests has dropped to the point where a number of computing magazines (e.g., Byte, PC Magazine) regularly publish the results of benchmark tests. Thus, a promising approach to constructing a hedonic function for microcomputers would use published benchmark test results as direct measures of system performance. In the conclusion of their paper, Berndt and Griliches take a step in this direction by stating:

> One item high on our research agenda involves obtaining model-specific performance measures for specific numerical tasks, such as the number of instructions executed per unit of time, and then re-doing our hedonic regressions with such performance measures added as regressors. Moreover, the issues of parameter instability and choice of variables to include in the set of characteristics are also potentially important, and need further examination.[23]

The second sentence makes reference to their specification of the hedonic function, which does not display stability in the estimated parameters over time. This issue is discussed below.

The data set includes 1265 model-observations. 72% of the model-observations are taken from list-prices, and the remaining 28% represent discount prices. This ratio does not reflect the proportion of sales in each market (in terms of number of units or of dollars), but rather the number of advertisements in the various sources. This "misrepresentation" of the microcomputer market is not a significant issue, as the final index constructed by the authors is weighted by revenue shares.

The regression is specified in a Log-Log form, and a Box-Cox test confirms this specification. The authors provide considerable insight on the interesting econometric issue that Time = Vintage + Age. If all three were continuous variables, all of them could not be introduced without exact multicollinearity. The choice of which variables to include affects the interpretation of all the regression coefficients; the article includes a discussion of the trade-offs and appropriate tests of parameter restrictions.

The "traditional" Time-Age (T-A) specification includes both time dummy variables and age dummy variables. Specifically, the time dummy variables T82, T83, ... , T88 and the age dummy variables AGE0, AGE1, AGE2, AGE3 are included. Using this specification, the estimated coefficients for the time dummy variables can be used to directly calculate a price index; this method is referred to as the "dummy variable method." Since the regression accounts for quality change holding time constant (i.e., quality in a given year is accounted for by the coefficients on the attributes of the microcomputer), the coefficients on the time dummy variables can be interpreted as capturing the unaccounted-for quality change over time. The interpretation of the age dummy variables not clear-cut, as they may represent either obsolescence or market selection effects.

The authors discuss the introduction of vintage dummy variables V79, V80, ... ,V88 to capture when a particular model was introduced. An alternative to the T-A specification

---

[23] Berndt and Griliches (1990), p. 35

is a Vintage-Age (V-A) specification, in which vintage variables are used instead of time variables. This specification will change not only the interpretation of the coefficients, but also the least squares estimates of the coefficients on the age and attribute variables. Given the clear interpretation of the coefficients on the time dummy variables, the T-A specification is preferred over the V-A specification.

However, some of the vintage dummy variables can be added to the T-A specification without encountering exact collinearity. Specifically, eight of the ten vintage dummy variables can be added, resulting in a Time-Age-Vintage (T-A-V) specification. If the first and last vintage dummies are eliminated, then the estimated coefficients on the remaining vintage dummies can be interpreted as the differences from the average rate of price decline embodied in vintages. The authors then recommend a specification test:

> We suggest that a necessary condition for a hedonic equation to be satisfactory is that the portion of quality change not captured by the characteristics variables should be unrelated to vintages, i.e., in a desirable specification, the α_v [estimated coefficients for the vintage dummy variables] should be approximately zero.[24]

Vintage variables can appear to be significant variables in a hedonic regression; the vintage coefficients can pick up strong effects if a significant proportion of user value is unaccounted for in the hedonic function, and this value is correlated with vintage. Vintage variables may pick up, for example, the effects of emerging standards for motherboard buses and disk drive controllers. While vintage variables may be a method of econometrically picking up these sources of user value, it would certainly be preferable to directly measure these sources of user value. Thus, the suggested specification test correctly assesses whether the specification of the hedonic function is adequately accounting for all sources of user value (i.e., that the estimated vintage coefficients are not non-zero).

This suggested test is certainly a useful baseline; however, this methodological discussion can be taken farther by asking the following question: why should either the age or vintage variables be significant? The market for PCs is unlike the market for cars or houses: a computer cannot be strictly associated with its year of introduction. One does not hear one's colleagues speak of their "'92 Compaq" or their "'97 Toshiba." The age or vintage of a computer is not a direct source of value consumers: when considering a purchase, most will not know (or care to ask) when it was introduced; nor does a computer in service undergo significant physical depreciation.[25,26] Rapid technological change does introduce a strong "obsolescence" effect that leads to negative asset price appreciation: over time, the price of a particular model will fall because the introduction of new generations of technology will put downward pressure on the price/performance ratio. Thus, the price of a "'92" Compaq 486 DX 33 (with a 500 MB hard drive) falls after its introduction, not because it's a "'92," (vintage) or because it

---

[24] Berndt and Griliches (1990), p. 14

[25] Being almost entirely digital, a computer is either working or not working; there is no gradual decline in its productive capacity. Industry folklore holds that a PC is most likely to experience a breakdown in the first 30 days of use, when covered by a warranty. Thus, computers do not depreciate in the same manner as other types of physical capital. Note, however, that depreciation is not a factor in a price index for new computers.

[26] The market for laptops is somewhat different, in that vintage becomes a significant proxy for a number of quality improvements. The specification of the hedonic function for laptop computers is discussed below.

is one year old, but because the introduction of newer, faster processors and components is pushing the technological frontier. Thus, a more restrictive specification test would require that *neither the vintage nor age variables be significant*. However, there is tension between a comprehensive approach to the hedonic function, which accounts for all sources of user value and would thus pass the vintage and age tests, and a more parsimonious specification of hedonic function, which may leave minor sources of user value unaccounted-for. If these omitted sources are correlated with age or vintage, then a "good" specification of the hedonic function may fail either or both of the vintage and age tests. The age restriction, though not close to being satisfied by this specification, is not wildly rejected either. In their pooled model, the authors find that only two of the three age variables are significant at the 0.05 level.

In their initial regression, the null hypothesis that the α_v coefficients are simultaneously equal to zero is rejected soundly on one of three criteria, and is very close to being rejected on the other two. Thus, the authors conclude:

> Hence, although the evidence is not clear-cut, we interpret these results as providing some support for the alternative hypothesis, and therefore admonishing us to assess our T-A specification in column 1 of Table 5 more closely, examining in particular what implicit parameter restrictions might be contributing to the rejection of the null hypothesis.[27]

By examining the parameters in the year-by-year regression, they notice that a number of parameters have trends: RAM, HRDDSK, and DOTHER have negative trends, while MHz has a positive trend. The authors experiment with two alternate specifications, an overlapping model with three separate regressions (covering the time periods 1982-84, 1984-86, and 1986-88) and a time-interaction specification that introduces time × attribute variables for the attributes mentioned above. Both of these specifications pass the T-A-V specification test, indicating that vintages are no longer significant in these revised specifications of the hedonic function.

The parameter instability results are not surprising when one considers the underlying data. For the RAM variable, the mean value increases by two orders of magnitude over the sample (from 94.92 in 1982 to 1069.39 in 1988); likewise, the mean value HRDDSK increases from 0.0 in 1982 to 43.64 in 1988. When such dramatic changes in the independent variables are taking place, it is reasonable to expect that their valuation will change over time. Indeed, the valuation must change, since the dependent variable in the regression (price) is virtually unchanged over the time period: a mean $3617.61 in 1982 versus $3508.47 in 1988. In a pooled specification, the only mechanism for price change is via the time dummy variable, which implicitly scales all attribute prices by the same factor in a given year. There is no theoretical or empirical justification to assume that technological innovation and market forces work at exactly the same rate for each of the sub-components of a PC system, so the pooled approach represents an implicit (and untested) restriction on the estimation procedure.

The authors conclude by calculating a number of price indexes. Using the dummy variable method, they calculate indexes using nine specifications. The range of estimates is -20.3% to -33.6% average annual growth rate (AAGR). If the three vintage

---

[27] Berndt and Griliches (1990), p. 22

specifications are eliminated, the range is narrowed to -27.9% to -33.6% AAGR.[28] This tight range of indexes for different specifications gives reasonable confidence that the results are not an artefact of the particular method of constructing the price index from the hedonic function.

The dummy variable indexes do not account for changes in the mix of models over time. Using data on shipments by model (950 model-observations) from the International Data Corporation, Divisia indexes that weight quality-adjusted prices of models by their revenue shares are calculated for a number of specifications. This index requires estimating prices for entering and exiting models, and is thus a "composite" or "imputation" index.[29] The two results for "all models" are indexes that show -28.2% and -28.0% AAGR for the pooled T-A and the overlapping T-A specifications, respectively. These "all models" indexes are the "broadest" type of index, in that they capture the price change embodied in entering, continuing, and exiting models.

As with all empirical studies, this one has limitations or room for improvement. As the authors acknowledge, two of the major areas for improvement are in the incorporation of improved performance measures (i.e., new independent variables) and improved specification of the other independent variables. This critique has discussed a few ways that these limitations could fruitfully be addressed.

Comments on Berndt, Griliches, and Rappaport (1995):

This paper accomplishes two objectives: (i) it updates the microcomputer price indexes of Berndt and Griliches (1990) with newer data; and (ii) it makes further developments on the issue of specification of the hedonic function with respect to the time, age, and vintage dummy variables.

The data on computer prices and attributes for 1988-1992 comes from a market research firm, DATAPRO, instead of magazine advertisements and reviews. One consequence of this shift is that the new study uses list prices, while the old took "street" prices into account. The effects of this change are ambiguous, as there are biases in both directions (i.e., greater or smaller rate of price decline). The authors discuss the change in data sources:

> In previous work, we used data from personal computer advertisements, such as those for mail-order purchases, to obtain measures of a particular model's characteristics and price. The advantage of this approach is that the resulting price data more closely approximates actual transactions prices than does, say, a list price. The disadvantage is that typical advertisements frequently provide less than full information on the particular combination of attributes 'packaged together' in the model by the vendor. The DATAPRO data set has the advantage of providing far

---

[28] Because the indexes from the vintage (V-A) specification have a different interpretation than the indexes from the age (T-A) specification, we would not expect their values to be identical. Thus, in assessing the degree of correlation between methods of constructing the price index, it is more meaningful to compare only the indexes resulting from the age specification.

[29] See Cole et al. (1988) for a discussion of "composite" indexes, Triplett (1988, 1989) for discussions of the "imputation method." Griliches (1971) also discusses the methods of using a hedonic function in the construction of a price index.

> more complete technical specifications than does the typical magazine advertisement; DATAPRO provides technical information on approximately 40 characteristics in a consistent form across manufacturers, models, and years. However, the price data from DATAPRO is for the list price of the particular base model, rather than a transactions price. Although in our previous study we found that 'street' prices where frequently 35% lower than list prices, whether this discount proportion has changed substantially over time is not clear. ...To the extent that percent discounts from list price to transactions price have increased as competitive pressures in the PC market have intensified in the past few years, the price indexes resulting from our use of DATAPRO data might understate somewhat the true rate of price decline of PC's. On the other hand, the share of sales accounted for by mail order models has plausibly increased since 1989. Since in the mail order market there is no apparent distinction between list and transactions prices, the use of list price data for the entire 1989-92 time period might overstate the average transaction price decline. Moreover, it is widely known that in 1992 major brand manufacturers changed pricing strategies and brought list prices down considerably to match others' transactions prices. Which of these various offsetting effects is dominant is, unfortunately, unknown.[30]

Perhaps the largest drawback to the shift in data sources is the resulting incompatibility of the two data sets. The 1982-1988 data cannot be linked with the 1988-1992 to provide a decade-long price index for microcomputers.

In specifying the hedonic function, the authors make use of some of the 40 characteristics available from the Datapro data set. For desktop models, numeric variables are: the quantity of RAM (in kilobytes); the maximum RAM the machine is capable of holding (MAXRAM); the speed of the CPU in MHz; the capacity of the hard disk, in megabytes (HDDSK); the volume of the case in cubic inches (SIZE); and the weight in pounds (WGT). Dummy variables specify: the age of the model in years (AGE0, AGE1, AGE2, AGE3); if two or more floppy drives are present (DFLP23); if no hard disk is present (DNOHDDSK); the instruction length of the processor (DPROC8, DPROC32); if the model is a portable or "laptop" computer (DMOBILE); the brand of the computer (Dxxx, where xxx is one of 12 companies); the year of the observation (T89, T90, T91, T92); and the vintage of the model (V86, V87, ... ,V92). By the specification of the dummy variables, the default model has a 16-bit processor, is made by an "other" manufacturer, and is not a laptop model.

To this specification a number of interaction terms are added: RAM*HDDSK; MHz*SIZE; and WGT*SIZE. Finally, the squares of a number of variables are included: RAM^2, $MAXRAM^2$, MHz^2, $HDDSK^2$, $SIZE^2$, and WGT^2.

The rationale for the inclusion of many of these variables is not discussed; it's difficult to interpret some of them as direct sources of user value (e.g., SIZE, WGT, WGT*SIZE,

[30] Berndt et al. (1995), p. 246-247

MHz*SIZE, $SIZE^2$, WGT^2).[31] Presumably, these variables are included as proxies for sources of user value, as the weight of a car has served as a proxy for its quality.[32] However, the process by which the size or weight of a microcomputer is a proxy for user value is not made clear.

Further, the introduction of the interaction and squared terms is similarly ill-discussed. A natural interpretation of some of these variables (e.g., RAM*HDDSK, RAM^2, MHz^2, $HDDSK^2$, and possibly $MAXRAM^2$) is that they are intended to capture the non-linear relationships between system components and the overall performance of a computer system. However, the rationale for these particular interaction terms is not discussed and does not appear to be based on engineering (or other) principles. Ultimately, a number of these terms cannot be interpreted as in any way being a measure or proxy of system performance, as they do not affect system performance: MHz*SIZE, WGT*SIZE, $SIZE^2$, and WGT^2.

"Results from preliminary regressions suggested that parameters differed significantly for mobile and desktop models, and thus we proceeded by disaggregating PC's into these two groups."[33] Thus, empirical tests confirm the intuition that the sources of value in desktop and portable computers differ significantly, and therefore must be addressed with separate hedonic functions.[34]

The results of the hedonic regression for desktops appear to be problematic in terms of assessing the sources of user-value. The restriction of parameter stability over time is rejected, and separate regressions must be run for each of the four years in the data set. Many of the variables highlighted as questionable above do not have significant results; of the 44 estimated coefficients, only 16 are statistically significant at the 0.05 level.[35] Thus, their inclusion appears to add little to the model. Furthermore, key variables with direct interpretation as sources of user value are frequently not significant: the estimated coefficients on RAM, MHz, HDDSK, PROC8, and PROC32 are significant at the 0.05 level in only seven of nineteen cases.[36] In four of the significant cases—for RAM and RAM^2—the signs of the variables reverse between 1989 and 1992. This significant parameter instability may simply be a result of fluctuations in RAM prices, but taken together, these results raise serious questions about the specification of the hedonic function.

It is the opinion of the author that there are three major problems with the specification of the hedonic function. First, a number of variables that are questionable sources of user

---

[31] Again, the specification for laptops is somewhat different. For laptops, the variables SIZE, WGT, and even density are all valid measures of user value.

[32] Even this classic proxy has mixed interpretation: while many attributes that provide utility to drivers also increase the weight of a car (e.g., air conditioning, automatic transmission, power steering, radio), weight is an inherently undesirable attribute of a car as it leads to increased fuel consumption. Thus, the interpretation of the coefficient on weight becomes equivocal. For this reason, it is desirable to include direct measures of the attributes that provide user value (whenever available) rather than to specify proxies for them.

[33] Berndt et al. (1995), p. 253

[34] Note that portable and desktop models were pooled in the 1990 version of the paper.

[35] Here, "questionable" variables in terms of user value are taken to be: RAM^2, $MAXRAM^2$, MHz^2, $HDDSK^2$, RAM*HDDSK, SIZE, $SIZE^2$, WGT, WGT^2, MHz*SIZE, and WGT*SIZE.

[36] While there are five "key" variables and four years suggesting 20 estimates, no models with 8-bit processors were recorded in 1992, thus eliminating one estimate.

value have been included. Unless a reasonable argument can be made for the inclusion of these variables on the grounds of user value, they should be eliminated. The resulting, more parsimonious model might render the remaining coefficients significant.

Second, at least two key sources of user value are not adequately measured. (i) The presence of a monitor, or any of its attributes, has not been noted. (ii) Major aspects of the performance of systems have not been measured. For example, no distinction has been made between 386 and the 486, (since both are 32-bit processors) despite the significant performance differences between the two. Likewise, as with the 1990 paper, the distinction between the SX and DX versions of the Intel processors is omitted. Finally the interaction effect of CPU generation and clock speed has not been captured.

Third, while the authors again employ a Box-Cox specification test, the resulting double-log functional form of the hedonic function is restrictive in that does not allow for a form of hedonic contour that may have prevailed in the microcomputer market by 1992.[37] As Triplett (1989) pointed out, if all producers have access to the same technology, then "t-identification" will occur.[38] Such a specification would allow concave (or bowed-out) hedonic contours, which the double-log specification does not permit. Thus, it may be worthwhile to explore the effects on the resulting price indexes that imposing a functional form consistent with t-identification would produce.

The specification for mobile or laptop computers is slightly different, and more satisfying; the resulting parameter estimates demonstrate stability over time. In addition, the parameters on the key sources of user value (e.g., RAM, HDDSK, COLOR screen, PROC8, and PROC32) are all of the right sign and are significant at the 0.001 level. Two major differences between the desktop and the laptop markets in terms of the sources of value are: (i) quality tended to be more consistently correlated with brand in the laptop market, and (ii) the presence of a colour screen in a laptop commanded a significant price premium. Thus, it's not surprising that the brand dummy variables and the COLOR variable are highly significant. In addition, the laptop market was evolving at a significant pace, as advances in a number of areas relating to miniaturisation were made in a number of areas: low-power processors, batteries with longer lives, the development of standards for expansion card (PCMCIA-II and -III) slots, modems, hard-drives, and displays. These innovations tended to have rapid and widespread adoption by laptop manufacturers, so these (unmeasured) quality improvements were closely correlated with the year of introduction of any specific model. Again, the significance of the year dummy variables is not surprising (D90, D91, D92). Overall, the capturing of major sources of value (COLOR and brand) and the year dummies as proxies for other quality improvements leads to a better specification in the laptop market. However, the concerns about performance measurement raised for desktops apply equally to laptops.

The econometric issues surrounding the Time = Vintage + Age identity are re-opened. A new, "saturated" model is developed, in which the time and vintage dummy variables are

---

[37] Hedonic contours are discussed more thoroughly in Chapter 3.

[38] As the PC industry gradually became less vertically integrated, PC makers shifted from being manufacturers of components and systems to being assemblers of standardised, interchangeable components (e.g., RAM, video cards, I/O cards, power supplies, keyboards, cases) plus a processor (typically supplied by Intel or a competitor according to a price schedule common to all customers). Thus, the likelihood that a single, common production function prevailed (at least approximately) has been increasing.

combined into time-vintage interaction variables: V86T89, V87T89, ... ,V92T92. In this specification, which does not include an intercept term, nine restrictions on the interaction variables must hold if the classic T-A model is to be valid. A new procedure for assessing the specification of the hedonic function is introduced.

As with the 1990 version, the authors perform a thorough job of constructing a variety of price indexes using data from the hedonic function (for both the laptop and desktop markets). Indexes are constructed using: arithmetic means; matched models; the dummy variable method and several specifications of the hedonic function, including the "saturated" specification; the characteristics prices method; and the imputation method with a Divisia index. The range of estimated AAGR for indexes that use the hedonic function is -25.6% to -36.59% for desktops, and -17.11% to -26.52% for laptops. Again, there is good convergence between estimated price indexes, indicating that the transition from a fitted hedonic function to a price index is reasonably robust to method.

Thus, the specification of the hedonic function for desktop personal computers is the only weak point in an otherwise very strong paper that, like the 1990 paper, contributes both empirically and with a revised specification testing procedure.

Comments on Nelson, Tanguay, and Patterson (1994):

This paper follows a similar approach to the previous two papers, but with a different emphasis. Here, the focus is clearly on the specification of the hedonic function, in terms of the choice of characteristics to be included, rather than on the theoretical development of econometrics as exemplified in the issues around the time-vintage-age specification question.

Following the approach of the 1990 Berndt and Griliches paper, the sources of data for this paper are computer trade publications (cited as *PC Week, PC Magazine, PC Resource, PC Today,* and *Tech PC Journal*).[39] This study examines only IBM-PC compatible desktop machines, allowing for a more focussed specification of the hedonic function. The sample is 1,841 observations over the period 1984-1991.

Using what appears to be a semi-log specification, the authors do a detailed job of specifying the attributes that account for quality in PCs. Quantitative measures include the CPU clock speed, quantity of RAM, hard disk capacity, the number of floppy drives, the number of expansion slots on the mother board, and the number of input-output (I/O) ports. Dummy variables include all generations of Intel CPUs (from the 8086 to the 80486, including the SX/DX distinction),[40] the presence of a colour or monochrome monitor, the presence of the DOS operating system, and the inclusion a software utility bundle. Rather than include dummy variables for individual brands, the authors use a single dummy variable for "major" manufacturers. The specification in this paper clearly reflects a knowledgeable approach to assessing the sources of user value in PC's, and has largely overcome the omitted variables problems identified above in discussing the previous two papers.

---

[39] It is not clear whether the data came from advertisements, technical reviews, or both. Likewise, the authors do not define a sampling strategy over the time period, so data may come from one month per year or from entire years.

[40] The dummy variable for the 80286 is omitted to avoid perfect collinearity.

The authors adopt a non-linear specification of the hedonic function that allows attribute values to vary over time in pooled model. This approach introduces attribute-time interaction terms, but constrains the annual change in implicit prices for a class of attributes (e.g., MHz) to be constant across the time period. Thus, the resulting model is considerably more parsimonious than estimating separate prices for each attribute class in each time period. However, these attribute-time interactions are largely found to be insignificant, and are dropped from the model. The significant time-attribute interactions are those for CPU clock speed (in MHz), RAM, hard disk capacity, I/O ports, and major brands. The R^2 for the pooled, linear model is 0.7943, which is evidence of good explanatory power. Although the linear model is rejected in favour of the non-linear model, the R^2 for the non-linear model is not presented.

The pooled specifications are compared to adjacent period regressions using the linear specification, for which a Chow test indicates that only one additional year pools with any two other years (1988 with 86-87). For the adjacent years specification, the R^2 range from 0.59 to 0.87, with 0.765 as the average. However, the adjacent years specification leads to "somewhat erratic changes in the sign and magnitude of the estimated coefficients;" this parameter instability leads the authors to reject this specification in favour of the pooled, non-linear specification.

Using this specification for the hedonic function, the authors calculate price indexes using the dummy variable, imputed prices, and characteristics prices approaches. Interestingly, the authors calculate separate indexes for major manufacturers versus mail-order manufacturers. The estimated indexes for major brands range from 18.46% to 20.24% average annual decline in quality adjusted prices; the range for mail-order brands is 25.91% to 26.44%.

While this paper provides a clean, sensible specification of the hedonic function, it too could be improved upon. First, the time period covered is relatively short, and perhaps misses significant innovations in the early market for PC's (1981-1984). Second, while the hedonic function is clearly an improvement over previous work, it still falls short on its measures of system performance. Here, performance is captured by two measures: a dummy variable for the generation of the CPU (e.g., 80386) and a measure of the clock speed of the CPU (e.g., 33 MHz). This treatment implicitly assumes that clock speed ratings are comparable across generations of processors and should, thus, have the same implicit price. Along these lines, the authors make comments, such as "The implied price of an additional ... MHz of speed ... fell by ... 61% [over the period 1984 to 1991]."[41] However, it is simply not sensible to compare a MHz of an 8088 to a MHz of an 80486 as a clock cycle in these dramatically different chip designs will allow for very different quantities of computing to be accomplished. Thus, the measurement of performance could be improved by either (a) including CPU generation by clock speed interaction terms or (b) directly measuring performance through benchmark test results. The mismeasurement of performance is a candidate explanation for the parameter instability that surfaced in the adjacent periods regressions. A third improvement to this paper would me a more detailed treatment of the functional form issue. In this paper, the authors appear to simply adopt the semi-log specification without testing of alternate functional forms. As has been noted above, this formulation does not permit bowed-out hedonic contours. A fourth and final area of concern is the lack of data on market sales.

[41] Nelson et al. (1994), p. 31

Ideally, sales data would be used as weights in the construction of price indexes. However, the authors note that in prior work, indexes making use of sales data (e.g., the Divisia index of Berndt and Griliches, 1990) are nearly identical to those that do not use sales weights.

Recent Work

A recent paper has examined the price change in the market for laptop PCs (Baker, 1997). This study uses data from an annual review of laptops published in *PC Magazine*, drawing data from the period 1990-1995. By and large, the author follows the specification for laptops used previously, including terms such as weight, volume, and density as sources of user value. The author makes an interesting choice in modelling performance, however: "In this study, only MHz is included as a variable for processor capability under the assumption that MHz is highly correlated with other characteristics represented by the type of chip." However, this data set includes four major generations of CPUs (from the 80286 to the Pentium), and forcing comparisons across different chip architectures using only MHz is "increasingly meaningless" according to industry sources.[42] While the assumption that MHz are correlated with the generation of CPU is true across the entire sample, within years the correlation is much lower as computers were available with different generations of CPU clocked at the same speed. Three versions of the price index are estimated, based on a pooled linear model, a pooled non-linear model, and an adjacent years linear model. The estimated AAGR's are: -25.7%, -33.1%, and -28.4%, respectively.

Summary

Quantifying the rate of quality-adjusted price change in microcomputers has proven to be a particularly challenging measurement task. Over time, methods have sharpened and understanding of the technology has grown. The state of the art in the specification of hedonic functions has even been advanced, as in the Berndt-Griliches-Rappaport discussion of the time = vintage + age issue. Even in recent work, however, the measurement of performance has not been adequately addressed. Until this issue is resolved, the measurement of price change cannot be said to have been handled adequately.

Improved Approaches to Personal Computer Price Indexes

As was argued above, microcomputers must be treated as complete systems. Thus, the issue of measuring user value would ideally be addressed by measuring the performance of the entire computer system. The performance of a computer system depends not only on the individual levels of performance of the components of the system, but also the interaction of these components. Two alternatives are to: (i) analytically model the performance of computer system using attributes of the components, and thereby derive an estimate of computer performance; (ii) directly measure the performance of computer systems on representative set of tasks—the approach of benchmarking discussed in detail in Chapter 3.

---

[42] See, for example, annual Ziff-Davis presentations surrounding new benchmark rollouts.

In critiquing the three principal efforts at price indexes for microcomputers (Berndt and Griliches, 1990; Nelson et al., 1994; Berndt et al., 1995), a number of suggestions were made regarding the specification of the hedonic function. These suggestions relate to two broad approaches: "technical proxies" and "benchmark." Both approaches, however, depend on a thorough understanding of microcomputers and their sources of value for users. As in the joint IBM-BEA work (Cole et al., 1986), good econometric results depend on an in-depth understanding of the technologies in question.

The technical proxies method follows the approach traditionally taken in hedonic analyses of computers, in which the independent variables in the hedonic function are technical attributes of the computer. The suggestions for improving a technical specification of the hedonic function are:

1. To separate IBM-compatible personal computers from other microcomputers for the purposes of analysis, allowing a cleaner specification of the hedonic function.

2. To make model the important distinctions between generations of processors, e.g., 8086 versus 8088 and 386 versus 486.

3. To treat performance in a meaningful way, recognising that a MHz of CPU clock speed is not homogenous across generations of CPU.

4. To obtain and include data on the monitors associated with systems.

5. To test a candidate set of other technical attributes for inclusion (e.g., hard drive interface).

6. To eliminate attributes that do not have a user-value interpretation (e.g., the volume of a desktop PC case).

7. To explore the implications of using functional forms that produce bowed-out hedonic contours.

The direct approach proposes to use more direct measures of user value, rather than technical attributes, as independent variables in the hedonic function. The candidate sources of user value include:

1. System performance, as measured by system-level benchmarks.

2. System capabilities, as captured by make and version of operating system.

3. Storage capacity, as captured by hard-disk space.

4. Display quality, measured by size and graphics standards supported.

Since there is no theory on which to base this candidate list, empirical study should be undertaken to confirm the sources of user value. Chapter 3 presents a detailed discussion of the methodology associated with the specification and estimation of the hedonic function in the context of computers. Included in this chapter are the results of an empirical study to assess the sources of user value in IBM-PC compatible microcomputers.

Chapter 3: Methodology

The most promising method to explicitly deal with quality change is the use of a hedonic function. Jack Triplett comments:

> Constructing price indexes for computer equipment is a challenge because these products have exhibited extremely high rates of quality change, and quality change presents one of the most difficult problems encountered in price index construction. Hedonic methods provide an advantageous alternative to conventional price index approaches for situations where quality change is encountered.[43]

Theory: The Hedonic Approach

The theoretical basis for the use of a hedonic function is the *hedonic hypothesis*: a heterogeneous good can be treated as an aggregation of homogenous attributes. The objective of empirical work is to fit a hedonic function to the data:

$$P = h(c) \tag{2}$$

where P is an n-element vector of prices of models of heterogeneous goods, and c is a $k \times n$ matrix of the (homogeneous) attributes.

The use of hedonic methods dates back to the 1920s. Although he did not use the term "hedonic," Frederick Waugh's empirical work relating the price of asparagus bundles at the Faneuil Hall wholesale market in Boston to their attributes (length, colour, number of stalks) was the first known use of a hedonic function (Waugh, 1928).

The term hedonic was coined in Court (1939), in work addressing automobiles. However, this work was not well-known, and hedonic methods remained obscure.

The person most responsible for bringing hedonic methods into the mainstream of the economic literature is Zvi Griliches (1961), who updated Court's work on automobiles, and considerably extended our understanding of hedonic methods. For this, and his subsequent work, he has been dubbed "The Father of Modern Hedonic Price Analysis."[44]

The use of hedonic functions in the construction of price indexes was initially resisted for a number of reasons (Triplett, 1990). The foremost criticism was that there was no theory behind the use of the hedonic function. However, in the three decades following Griliches (1961), much was added to our understanding of the hedonic function.

Rosen (1974) showed that, in general, the hedonic function is an envelope function of either the users' value function or the producers' cost function. As with any envelope function, the form of the hedonic function is independent of the forms of the user

---

[43] Triplett (1986), p. 36

[44] See, for example, Berndt (1991), pp. 115-116

preferences or producer costs underlying it; instead, it is determined by the distribution of buyers and sellers across characteristics space. Thus, the form of the hedonic function in any particular context is a purely empirical matter.

Triplett (1983, 1987) took the necessary step of extending index number theory from goods space to characteristics space. He showed that a hedonic price index can be thought of as an approximation of an exact characteristics subindex (i.e., the ratio of the costs of two constant-utility heterogeneous goods under different characteristics price regimes), provided that the utility function is separable between the attributes of the heterogeneous good and quantities of other, homogeneous, goods.

The state of understanding of the theory of hedonic price indexes, as they relate to computers, is summarised in Triplett (1989); the following list draws from this summary, and maintains the original numbering of results.

(1) If there are n competitive buyers, with dispersion in using technologies, the hedonic function, $h(\cdot)$, will trace out an envelope to the set of using technologies, $q_1(\cdot),\ldots,q_n(\cdot)$. As with any envelope, the form of $h(\cdot)$ is independent of the form of $q(\cdot)$—except for special cases—and is determined on the demand side by the distribution of buyers across characteristics space.

(2) If there are m competitive sellers, with dispersion in producing technologies, the hedonic function, $h(\cdot)$, will trace out an envelope to the set of producing technologies, $t_1(\cdot),\ldots,t_m(\cdot)$. In parallel with the user case, the form of $h(\cdot)$ is influenced on the supply side by the distribution of sellers across characteristics space, but the form of $h(\cdot)$ cannot in general be derived from the form of $t(\cdot)$.

(3) As a consequence of results (1) and (2), the form of the hedonic function, $h(\cdot)$, is in the general case purely an empirical matter. In particular, and despite many statements to the contrary that have appeared over many years, nothing in the theory rules out the semi-logarithmic form, which has frequently emerged as "best" in functional form tests in the hedonic literature (Griliches, 1971).

(4) Special cases exist in which $h(\cdot)$ can be "identified," in the econometric sense, either by seller or buyer technologies. If the using technology, $q(\cdot)$ is identical for all users, the form of $h(\cdot)$ is determined by the form of $q(\cdot)$, and should conform to the principles of classical utility or production theory. If the producing technology, $t(\cdot)$, is identical for all sellers, the form of $h(\cdot)$ is determined by the form of $t(\cdot)$, and the usual reasons apply for assuming convexity of production output sets.

(5) An *input-cost index* (ICI) is an exact index that shows the minimum change in cost between two periods that leaves output unchanged—i.e., the ratio of costs of optimal points on the same production

isoquant under two input price regimes. It is the production-side analogue to the more familiar notion of the cost-of-living index, on which the literature is voluminous.

(6) When extended to characteristics space, the full ICI depends on all the inputs in $Q = Q(c, Z)$—the homogenous inputs, Z, and the characteristics, c, of heterogeneous inputs; it also depends on the form of the hedonic function, $h(\cdot)$, and on the form of the production function, $Q(\cdot)$—Triplett, 1983. The full ICI is an exact characteristics price index.

(7) Generally, the full ICI is intractable. For the separable production function $Q = Q(q(c), Z)$ an exact "subindex" can be computed that involves only computer characteristics. This "computer price index" is the ratio of costs, under two characteristics price regimes, of two constant-output collections of computer characteristics. The subindex is also an exact characteristics price index, and it is a "constant quality" or "equivalent quality" price index because the two collections of computer characteristics implied by it are equivalent in production. It is a price index for the capital services provided by computers when they are used as the inputs in the production for something else (or, indeed, in the production of other computers).

(8) The hedonic price index for computers—a calculation based solely on $h(\cdot)$—can be thought of as an approximation to the exact characteristics subindex, provided conditions necessary for the exact subindex are met—that is, the production function can be written as $Q = Q(q(c), Z)$.

(9) An exact *output price* index is an index composed from the ratio of costs of optimal points on a single production possibility curve under two price regimes.

(10) The characteristics-space from the *exact* output price index for computers is the ratio of two points taken from a particular value of the transformation function, $t(.)$, in $t(c, K, L, M) = 0$—that is, it is a price index constructed from collections of computer characteristics that can be produced with the same resource cost. It is an exact characteristics price index and is a "constant quality" price index in the sense defined in Triplett (1983, pp. 289-299).

(11) A hedonic price index for computers—that is, a price index derived solely from the hedonic function, $h(\cdot)$—can be thought of as an approximation to the exact output price index for computer characteristics. This result is parallel to result (8).

(12) In view of some confusion that exists in the hedonic literature, one should note that in the general case the hedonic index is *neither* of the exact (characteristics) indexes. The hedonic index depends

solely on the hedonic function; the functional form of the hedonic index thus depends on the form of the hedonic function, which is in general independent of the form of both using and producing technologies—see result (3). The exact index, on the other hand, requires information on the technology on the relevant side (e.g., using technology for the ICI) *and* the hedonic function (Triplett, 1987). For the special cases noted in result (4), the hedonic index will coincide with one of the exact indexes, but will differ from the other exact index. For example, if producing technologies, $t(\cdot)$ are identical across producers, the hedonic function will map the producing technology; in this case the hedonic index is the exact output price index for characteristics, but it is *not* the computer user's exact input-cost index.

(13) Because a long, and sometimes acrimonious, debate over "resource-cost" and "user-value" approaches to quality change has taken place over many years, a brief summary of the current understanding of this matter may be helpful. The *output* characteristics price index—result (10)—is defined on a fixed value of the transformation function, $t(\cdot)$, the position of which, technology constant, depends on resources employed in production; accordingly, "constant quality" for this index implies a resource-cost criterion. On the other hand, the *input-cost* index described in result (7) is defined on a fixed (user) production isoquant; for the ICI, "constant quality" implies a *user-value* criterion (an extended discussion is contained in Triplett, 1983).[45]

While the debate over the theory and the interpretation of the use of a hedonic function in the construction of price indexes has been long and technically sophisticated, the empirical application of a hedonic function is straightforward. Estimating the hedonic function, $P = h(c)$, is simply a matter of running a single regression. The prices of the goods (P) are regressed on the characteristics of the goods (c).

However, an excellent understanding of the class of goods being examined is necessary to make intelligent choices about two key questions: the set of characteristics to be included, c, and the functional forms to be tested, $h(c)$ (Griliches, 1971; Triplett, 1986, 1989). For an (input-cost) index for computers, this requirement amounts to having an understanding of the sources of user value derived from computers, and testing for all reasonable functional forms that might arise from the interaction of buyers and sellers in the computer industry.

The Matched-Model Method

The traditional method of accounting for quality change is the matched-model method.[46] Like all methods, this tracks the prices and attributes of a number of models of a good

[45] For the complete discussion, see Triplett (1989), pp. 128-133; his summary draws on work in Rosen (1974) and Triplett (1983, 1987).

[46] For a review of the origins of measuring quality change, see Diewert (1990).

across time. When the same model (i.e., a good having exactly the same attributes) appears in two time periods (a "match"), any difference in the prices for the model must be a pure price change, and is not attributable to quality changes. This technique does not make use of a hedonic function, and forms a good basis for comparison with hedonic methods.

The price index, $I_{1,t}$, for time 1 to time t is given by

$$I_{1,t} = \frac{\sum_{i=1}^{m} P_{i1}}{\sum_{i=1}^{m} P_{it}} \tag{3}$$

where P_{it} is the price of model i at time t, and m is the number of matched models between time 1 and time t. If x_1 and x_t denote the total number of models observed at time 1 and time t, then

$$x_1 + x_t = l + m \tag{4}$$

where l is the number of unmatched models.

If data on the sales of models in each time period are available, then the prices can be weighted. A Paasche specification of the matched model index is

$$I_{1,t} = \frac{\sum_{i=1}^{m} P_{it} S_{it}}{\sum_{i=1}^{m} P_{i1} S_{it}} \tag{5}$$

where S_{it} are the sales of model i at time t.

Because computer models change rapidly, it is customary to construct indexes for two adjacent years, and use a multiplicative chain of adjacent year indexes to calculate and overall index. This "chain index of matched models" is given by

$$I_{1,t} = I_{1,2} \times I_{2,3} \times \ldots \times I_{t-1,t} \tag{6}$$

The matched-model method relies on the assumption that the rate of price change of unmatched models equals that of matched models. To be more explicit, it requires that the rate of price change due to new goods (which will not match because they do not exist in the previous period) and discontinued goods (which do not match because they do not exist in the current period) is equal to that of goods that remain in the market. If the market for the good is in equilibrium, or has a slow rate of innovation (i.e., introduction and discontinuation of goods), then this assumption is tenable.

This method suffers from two possible sources of bias: (i) unmatched models I, and (ii) declaring non-identical (but similar) models to be a match. The higher the proportion of unmatched models, the greater potential that the true rate of price change will not be captured by the matched models. A recent study of microcomputers was able to match less than 20% of models, indicating that non-matches were a significant source of potential bias (Berndt, Griliches, and Rappaport, 1995). The second source of bias comes when models that are not identical (in terms of characteristics) are matched. The degree of difference in the characteristics of the models that are matched is a source of bias. Note that the two sources of bias are not independent, but are inversely related, since reducing the bias associated with imperfect matches due to tighter criteria for declaring a match will result in more unmatched models.

The question to what extent the matched-model method suffers from bias in the market for computers is, of course, an empirical question. Studies that have compared the matched-model method to other methods have found that the matched model method significantly understates the rate of price decline for both mainframe and microcomputers (Cole et al., 1986; Dulberger, 1989; Berndt et al., 1995). It is the inability of the matched-model method to capture rapid quality change that necessitates the use of hedonic methods.

The Dummy Variable Method

The simplest way to use a hedonic function in the construction of a price index is to include dummy variables, one for each year but the base year, in the hedonic function.

$$P = h(c; d_2, \ldots, d_n) \tag{7}$$

where n is the number of time periods (typically years) included in the data set, and d_i is the dummy variable for time i.

When the hedonic function is estimated, quality change will be controlled for by the coefficients on the set of characteristics (c) used to specify the heterogeneous good. Thus, the unaccounted-for price change will fall on the dummy variables, and the rate of price decline can be estimated directly from the coefficients on these variables.

In a double-log specification, the regression equation is

$$\ln P_{it} = \sum_{j=1}^{k} a_j \ln c_{ij} + \sum_{t=1}^{n} a_t d_t \tag{8}$$

where P_{it} is the price of model i at year t, and c_{ij} is the quantity of attribute j possessed by model i.

Thus, the a_j coefficients account for the importance of attributes in determining the prices of the heterogeneous good; these coefficients can also be used to calculate the implicit prices of attributes (see below). The a_t coefficients capture the price change not accounted for by quality change at time t, except for a_1, which is interpreted as the normal intercept parameter.

The price index is computed by taking the anti-log of the estimated a_t coefficients. A correction factor of one half of the estimated coefficient's squared standard error must be added, because "It is well-known that the anti-log of the OLS estimate of a_t is not an unbiased estimate of the anti-log of a_t...."[47] Thus, the price index is given by

$$I_{1,t} = e^{a_t} + \tfrac{1}{2}(\text{std err } a_t)^2 \tag{9}$$

The dummy variable method suffers from several limitations: (i) it imposes a constant set of implicit prices across all periods; (ii) it is not well-integrated with the rest of index number theory; and (iii) it typically uses price data unweighted by sales, and is therefore sensitive to the sample selection (Griliches, 1971; Triplett, 1989). Besides its simplicity, the chief advantage of the dummy variable method is that it allows one to ignore the problem of multicollinearity between the independent variables; as long as the combined effect of the explanatory variables is relatively stable across years, it does not matter if the coefficients on a particular attribute fluctuate. On balance, The dummy variable method is the least preferred way to make use of a hedonic function in the construction of a price index.

The Characteristics Index

A hedonic function can be used to estimate implicit prices for characteristics. Indeed, these implicit prices have been considered one of the most important results of hedonic analysis (Triplett, 1986). Again assuming a double-log specification, the price of characteristic j for model i in year t is given by

$$\hat{P}_{ijt} = a_j \frac{P_{it}}{c_{ij}} \tag{10}$$

These characteristics prices are then weighted by the quantities of characteristics sold, and the (Paasche) price index between time 1 and time t is given by

$$I_{1,t} = \frac{\sum_j \sum_i \hat{P}_{ijt} c_{ij} S_{it}}{\sum_j \sum_i \hat{P}_{ij1} c_{ij} S_{it}} \tag{11}$$

The characteristics price index has a good deal of appeal, in that it corresponds closely to index number theory (results 7 and 10). The characteristics price index was the first hedonic method adopted by a government agency, in the Census Bureau's "Price Index of New One-Family Houses Sold" introduced in 1968 (Triplett 1990). Triplett (1989)

[47] Triplett (1989), p. 162

considers the characteristics index to be one of the two preferred methods for incorporating a hedonic function in the construction of a price index.

The Composite Index

The "composite" or "imputation" method is based on the matched-model method, in that it uses observed prices for models whenever they are available. For new models or discontinued models, the hedonic function is used to estimate the unobserved prices: for new models, the reservation price in the previous period (before the model was introduced) is estimated; for discontinued models, the price in the current period is estimated. Using the set of observed and estimated prices, the price index is constructed.

The choice of base year for quantity weights becomes especially important. For example, a Paasche index, which uses current year quantity weights, needs to estimate for models introduced in year t (new models) the price in year 1. If a model that appears in both year 1 and year t is indexed with "i" and a new model (that exists in year t but not year 1) is indexed with "k," then the price index is given by

$$I_{1,t}^{P} = \frac{\sum_{i=1}^{m} P_{it} S_{it} + \sum_{k=1}^{l} P_{kt} S_{kt}}{\sum_{i=1}^{m} P_{i1} S_{it} + \sum_{k=1}^{l} \hat{P}_{k1} S_{kt}} \qquad (12)$$

Because of the Paasche specification, it is not necessary to estimate the price of discontinued models, as their quantity weight would be zero. However, if a Laspeyres index is constructed, it is necessary to estimate the prices of discontinued models, while new models will have no weight. Again denoting models that exist in both years with an "i," but now denoting discontinued models (i.e., models that exist in year 1 but not in year t) with "k," the index becomes

$$I_{1,t}^{L} = \frac{\sum_{i=1}^{m} P_{it} S_{i1} + \sum_{k=1}^{l} \hat{P}_{kt} S_{k1}}{\sum_{i=1}^{m} P_{i1} S_{i1} + \sum_{k=1}^{l} P_{k1} S_{k1}} \qquad (13)$$

By examining the difference between equation (12) and equation (13), we observe "...the somewhat odd result that Laspeyres and Paasche forms of the imputation index differ in the *prices* included in them, and not only in the weights, as in conventional cases."[48]

In comparing the methods, Triplett notes:

[48] Triplett (1989), p. 163, author's italics

> Compared with the other two [dummy variable index and characteristics index], the imputation method permits maximum utilisation of *observed* prices, thereby minimising measurement error from misspecification of the hedonic function, mismeasured characteristics, and so forth. Set against this is the potential bias that results because either new or discontinued models must be excluded from the comparison, at least when a fixed weight index is computed.[49]

The unusual version of the Paasche-Laspeyres problem is an ideal opportunity for the application of a superlative index (Diewert, 1976). A superlative index allows for the inclusion of quantity weights from both periods. For example, the Fisher ideal index is the geometric mean of the Paasche and Laspeyres indexes:

$$I^F_{1,t} = \left(I^P_{1,t} \times I^L_{1,t}\right)^{\frac{1}{2}} \quad (14)$$

A superlative index requires that imputed prices for both new and discontinued models be incorporated in the price index, and thus eliminates the bias due to missing models. The combination of the imputation method with a superlative index is robust to measurement error, misspecification, and makes maximum used of available data; hence, it is the most preferred method of price index construction.

Divisia Index

Berndt and Griliches (1990) devise a Tornqvist approximation to the Divisia index, in a double-log specification. This index, like the composite index, uses market share information and "degrades" to the matched model procedure for all models that are observed in both time periods. However, this model avoids the Paasche/Laspeyres problem by using average share weights across the two periods. As with the composite index, the prices of new or exiting models are estimated using the coefficients derived from the hedonic function. For the purposes of calculating "average" shares of entering and exiting models, the share for the missing data point is set to zero, effectively using half of the observed share as the weight.

Thus, the Berndt and Griliches operationalization of the Divisia index preserves all of the desirable qualities of the composite index while avoiding the Paasche/Laspeyres problem in the manner of a superlative index.

Practically, however, the Divisia index has not substantively varied from indexes that do not utilise share weights. For example, compare the average annual growth rate (AAGR) of the estimated Divisia index to the AAGR produced using the pooled dummy variable approach for laptops produced by Berndt and Griliches (1990): -23.90% versus -23.81%. Likewise, the comparison of AAGR's for desktop machines from the same study is -31.93% versus -32.13%.

---

[49] Triplett (1989), p. 165, author's italics

Choice of Attributes

The chief danger of using a hedonic function is that it is terribly easy to mis-specify the set of attributes (c) used to measure quality. Triplett (1986, 1989) suggests that the independent variables included in the hedonic function should meet three requirements:

1. They are homogeneous economic variables

2. They are building blocks from which heterogeneous goods are created

3. They are valued by *both* buyers and sellers

While, ideally, all of the variables should be valued by both buyers and sellers, this requirement cannot always be met. Result (13) above makes the distinction that the appropriate focus (user-value or resource-cost) depends on the type of index being constructed (output characteristics price index or input-cost index, respectively). This result can guide the choice of attributes when there is a trade-off (e.g., due to multicollinearity) between measures of user-value and measures of resource-cost.

However, the inclusion of characteristics that capture neither user-value nor resource cost is not uncommon; examples include the number of ice-cube trays included with a new refrigerator or the weight of a new car. Such variables can be useful when they serve as a proxy for real but unmeasured (or immeasurable) quality characteristics. "Use of a proxy variable, however, introduces the possibility of error whenever the relation between the proxy and the true variables changes, and one can never be entirely sure whether such shifts have occurred."[50]

The use of variables that measure neither resource-cost nor user-value introduce the usual problems of wrong regressors. "Such variables typically have been introduced into hedonic functions either because the researcher ignored the principle that variables in the hedonic function should have a technical interpretation, *did not understand the technology sufficiently to specify it correctly*, or perhaps lacked data on the true characteristics."[51]

Specification of the Hedonic Function

Triplett's criteria provide conditions to ensure that attributes in an hedonic analysis are meaningful economic variables. Unfortunately, these criteria do not provide any guidance in *identifying* these variables. Methods for identifying relevant attributes, in increasing order of rigor, include:

1. **"Regression Fishing:"** All attributes are thrown in the regression, and the researcher fishes for the most significant ones. This method may not be viable due to multicollinearity.

2. **Marketing theory on attribute driven advertising:** The vast majority of microcomputer advertisements are of the variety labelled "attribute-driven."

[50] Triplett (1986), p. 39

[51] Triplett (1986), p. 39, italics mine

Thus, one would expect attributes that are sources of user value would be consistently listed in microcomputer advertisements; conversely, attributes that tend not to be listed in advertisements are unlikely to be sources of user value.

3. **A conjoint analysis:** Groups of computer users are asked to rank a list of attributes. These rankings are subject to a factor analysis to identify the underlying (number of) factors and the attributes with which they are associated.

4. **A Delphi survey:** Through repeated sampling of domain experts, consensus is achieved as to the most important attributes in microcomputers.

Method 1 is clearly unsatisfactory because it lacks a theoretical foundation and is based on unsound methods that do not control for type I and type II error.

Method 2 has at least a theoretical grounding, but is unlikely to arrive at a perfect list of attributes. For method 2 to do so, two conditions would have to be met: (i) the majority of microcomputer manufacturers have a understanding of which attributes contribute to user value and include all of these attributes in their advertisements; and (ii) the majority of microcomputer manufacturers would have to refrain from including any other attributes in their advertisements. It is the opinion of the author that condition (i) is much more likely to hold than condition (ii). Reliance on this method may therefore lead to the inclusion of variables that are not associated with user value.

However, so long as condition (i) is met, method 2 can serve as a check on another method. Candidate attributes from another method should be checked to see that they satisfy the criteria of method 2: they are included in a majority of advertisements. Attributes failing this test are unlikely to be sources of user value.

Methods 3 and 4 display an equally high level of rigor. Method 3 draws on a technique often used by marketers to identify the attributes of a heterogeneous good that are most important to consumers. The four stages in a conjoint analysis are: (i) a sample of consumers is asked to rank the importance of each of a list of attributes of the good; (ii) a factor analysis of the results provides a reduced list of underlying attributes that are important; (iii) another sample of consumers undergoes a binary choice experiment that involves choosing between hypothetical goods with varying levels of the attributes;[52] and (iv) the conjoint analysis uses these choices to construct an estimate of how important each of the attributes is to the consumer population. However, the results are ultimately dependent on the initial list of attributes, which was created using the judgement of the researchers. Thus, the possibility of omitting relevant attributes still exists.

A conjoint analysis has the benefits of being based on consumer choice and producing an estimate of the importance of attributes to the consumer population. Thus, the output of a conjoint analysis is very similar to the output of a hedonic analysis: an empirically derived quantification of the importance to consumers of the attributes of a heterogeneous good. Thus, a hedonic analysis and a conjoint analysis should be considered to be substitutes, rather than complements. It would be interesting to compare the results of the two methods to see how similar are the results of the two

---

[52] A binary choice experiment presents a consumer with two hypothetical goods, A and B. The attributes of each of A and B are detailed for the consumer, and the consumer is asked to choose which good he prefers.

empirical techniques (consumer choice experiments versus econometric analysis). Conjoint analysis has one major practical drawback, however: it may require a large sample for stage (iii), depending on the number of attributes identified as important in stage (ii).

Method 4, the Delphi Survey, involves three stages: (i) choosing one or more samples of microcomputer experts; (ii) asking these experts to identify a candidate set attributes; and (iii) an iterated ranking of these attributes until consensus has been achieved within the sample. Provided that a sample with legitimate expertise can be identified, a Delphi survey has been shown to be a method of soliciting the combined expertise of a group while avoiding many of the pitfalls associated with face-to-face interaction.

Given the objectives and constraints of this research project, the Delphi Survey was judged the most appropriate technique for identifying and ranking the candidate attributes for inclusion in the hedonic analysis. The methodology underlying this survey, as well as its results, are presented below.

Functional Form

The functional form issue is discussed thoroughly by Triplett (1989):

> Four functional forms appear as computer processor hedonic functions: linear, semi-log, double-log, and translog. Most computer researchers have chosen the double-log functional form out of *a priori* conviction, rather than by testing alternatives.[53]
>
> This empirical work is unsatisfactory for three reasons: (1) The number of functional forms considered was limited, and excluded a class of functional forms that the theory of hedonic functions shows is plausible--namely, those with contours shaped like P_1P_1 and P_2P_2 in figure 4.1. (2) Even among the functions forms that were tried, no researcher has tested the entire panoply; many of the tests involved only two alternatives. (3) Finally, and perhaps most seriously, researchers who have looked at the functional form question have been content to carry out minimal goodness of fit tests, and then proceed to the empirical work using a chosen functional form. No one has worried very much about the sensitivity of estimated hedonic price indexes to what is essentially an arbitrary specification of functional form.[54]

In his discussion of the functional form of the hedonic function, Triplett notes that different functional forms will prevail if either of two special cases can prevail: if all producers have the same technology, then "*t*-identification" will occur; if all users have identical use technologies (or utility functions), "*q*-identification" will occur. In these special cases, it is possible to make inferences about the form of the hedonic contours: *t*-identification leads to hedonic contours that are bowed-out from the origin, *q*-identification to hedonic contours that are bowed-in toward the origin.

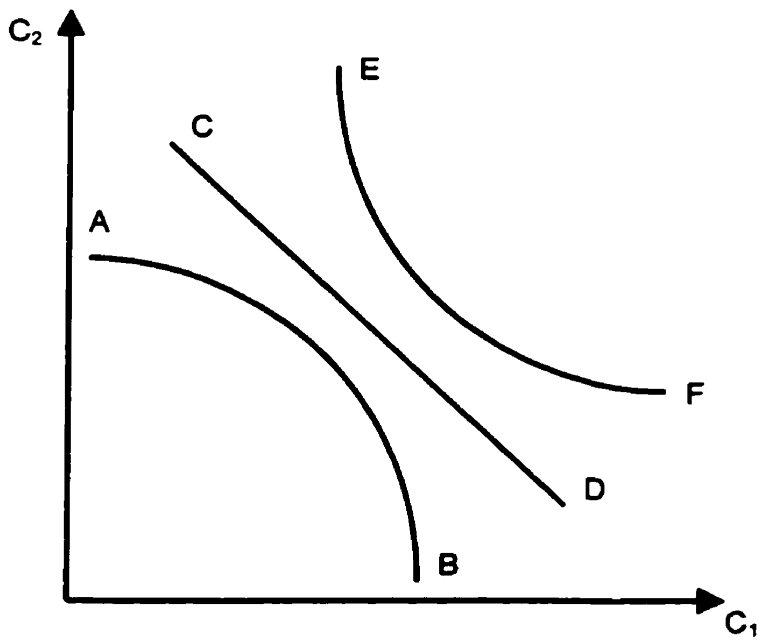
---

[53] Triplett (1989), p. 154
[54] Triplett (1989), p. 155

> The *t*-identification case has a great amount of economic appeal as a description of the computer industry; regrettably, none of the computer studies, even those that make use of flexible functional forms to choose among nested functions, test for a functional form consistent with *t*-identification. The hedonic functions considered were those with linear hedonic contours (linear and semilog hedonic functions) or those with bowed-in toward the origin contours (double-log hedonic function). None of the functional forms so far employed permits hedonic contours of bowed-out form, which leaves a considerable gap in our knowledge.[55]

Figure 2 depicts a range of hedonic contours for a good with two attributes. The axes represent the quantities of attributes C_1 and C_2 embodied in the heterogeneous good. Contour **AB** is "bowed-out" from the origin (as with a typical multi-attribute production or transformation function) and consistent with *t*-identification. Contour **CD** is linear, and can be produced by linear or semilog hedonic functions. Contour **EF** is "bowed-in" toward the origin, and can be produced by double-log hedonic functions.

Figure 2: Hedonic Contours



Triplett's criticism of previous research does not include Berndt and Griliches (1990) and Berndt et al. (1995) because it predates both. Indeed, both papers perform a Box-Cox specification test that confirms the double-log specification. However, neither of the papers examine the effects (on the resulting price index) of specifying a hedonic function that meet's Triplett's criterion for *t*-identification.

---

[55] Triplett (1989), p. 157

Delphi Survey

In the absence of "theory" about the sources of user value in microcomputer systems, an empirical assessment was undertaken to provide justification for the choice of attributes included in a hedonic analysis. Through a series of iterated surveys, two groups of experts identified and rated the importance of the characteristics of PC systems that should be considered during a purchase decision.

Delphi Methodology

"Project DELPHI" was carried out in the 1960's by two scientists at the RAND corporation, Olaf Helmer and Norman Dalkey, as a deliberately mediated method of obtaining opinion from a group of experts.[56] Initially developed in the context of estimating the number of nuclear strikes necessary to reduce US munitions output by 75% (Dalkey and Helmer, 1963), the method has been adapted and generalised (see, for example, Delbecq et al. 1975; Kendall, 1977; Adler and Ziglio, 1996). The objective of a Delphi survey is to utilise the judgement of a group of experts while avoiding some of the problems involved in face-to-face interactions. Such problems can include premature convergence to a candidate solution (the so-called "groupthink" phenomenon), the effects of dominant personalities, and more practical issues such as the difficulty of assembling a group of experts for a same-time, same-place interaction.

For these surveys, we followed the multiple-rounds process, taking account of recent prescriptions for running separate but related samples (Delbecq et al. 1975; Schmidt, 1997). In the first round, participants were asked to identify the characteristics of "PC Systems" (defined below) that were most important to consider in the purchase decision. In subsequent rounds, their responses were summarised and distributed anonymously to the rest of the group. In rounds 2 and 3, respondents rated the importance of each of the characteristics identified in round 1. After the second set of rankings, statistical tests indicated that a reasonable degree of consensus had been achieved within each group.

Pilot Test

Because the survey was to be primarily conducted via the Internet and/or by fax (at the participant's discretion), the underlying technologies, as well as the survey instruments, were pilot tested with a sample of undergraduate students. Participants were solicited from the core undergraduate IS course in the Faculty of Commerce and Business Administration at the University of British Columbia. The question was modified slightly for the pilot test to address "home use" of PC systems, rather than "business use" as in the final surveys.

For participants using the web, an e-mail message alerted them when a round of the survey was to be completed. This message included a unique URL address that pointed them to the host machine, and also used an embedded key to log that user into the survey. For example, the URL:

```
http://ITValue.commerce.ubc.ca/Welcome.asp?QL=D1R1P140K17203
```

---

[56] Here "Delphi" is treated as a proper noun rather than capitalized as an acronym.

identifies participant number 140, for round 1 of survey 1. The code "17203" is unique to this participant, round, and survey, and is mathematically derived from key attributes in the underlying database. (Users could also go to the home page for the survey, and enter their ID and password to log into the appropriate round of the survey.)

The survey was implemented using active server pages running from an Access 97 (SR-2) database, using a Delphi.DLL developed in Visual Basic 6.0. The host machine was a 300 MHz Pentium-II with 256 MB of RAM running Windows NT (4.0). The pilot test showed that the server was more than adequate to handle the survey and any reasonable number of concurrent users. The pilot revealed a problem with the algorithm that had been designed to generate unique keys, which would cause an overflow error in Access in later rounds of the survey. The algorithm was modified to avoid this problem prior to the roll-out of the final surveys.

The pilot also revealed a wide variance in interpretation of the question, which initially asked respondents to identify "sources of user value" in PC systems. The question for the final surveys was modified to ask about "characteristics" of PC systems, anchored in the context of the purchase decision.

Samples

Two sample frames were used for these surveys. The first group, IS managers, were selected from members of the Canadian Information Processing Society (CIPS). CIPS shared the mailing list for its British Columbia membership. From this list, faculty members at the University of British Columbia and Simon Fraser University were removed, owing to their exposure to this research at earlier stages. The resulting sample frame contained 385 individuals. The first contact with the IS Managers was a one-page fax that introduced the research and invited them to participate in the study. (The instruments used in the survey are presented in Appendix 2.) Using the fax numbers in the CIPS mailing list, invitations were successfully sent to 310 individuals. From these 310 invitations, 80 responses were received, yielding a response rate of 25.8%. From these 80 responses, 33 individuals were chosen to participate in the Delphi survey. These individuals had at least 5 years of experience using PC systems, and at least 3 years experience managing end-users' use of PC systems.

The second sample frame was business "power-users" of PC systems. These individuals worked outside of an IS department, but were considered by their IS managers to have a good understanding of PCs. Using a snowball sampling procedure, the business users were identified by the IS managers. In total, 31 business users were identified. Of these, 22 were selected who had at least 5 years experience using PC systems.

Ultimately, 29 IS managers and 20 business users completed the survey. On average, the CIPS respondents had been using PCs for 15.3 years, and had been supervising end-users in the PC or Client/Server environment for 9.8 years. The business users represented a number of functional areas, with finance, accounting, and marketing being most common. On average, the business users had 12.3 years experience working with PCs, and 75% of them had been involved with developing or customising application software. Both groups had experience with multiple generations of PCs and multiple generations of operating systems. These demographics provide assurance that both samples have sufficient expertise with PCs and the general business environment.

Results

The surveys were run such that respondents had one week to respond to each round of the survey. Following the suggested procedure of Schmidt (1997), the two surveys were run together for the first round. In this round, respondents were asked the following question:

Round 1 Instructions

> The purpose of this questionnaire is to draw on your experience with IBM-compatible personal computer (PC) systems to evaluate the most important sources of business value.
>
> **For the purposes of this study, a "PC System" includes:**
>
> - **The PC itself** (CPU, RAM, hard disk, motherboard, video card, etc., and possibly modem or network cards)
> - **Monitor**
> - **Standard peripherals** (keyboard, mouse, and possibly speakers)
> - **Operating System**
>
> **Please note:** a "PC System," as defined here, does **not** include **applications software or other peripherals** (e.g., a printer or scanner).
>
> For this round of the survey, we would like you to answer the following question:
>
> **Imagine that you have been asked for advice on the purchase of PC systems for business use. In your opinion, what are the most important characteristics of PC systems to consider in the purchase decision?**
>
> Note: A **"characteristic"** may apply to an entire PC system, or only to a component of that system. In the context of evaluating photocopiers, for example, a system-level characteristic could be "pages copied per minute" or "warranty," while a component characteristic could be the "size of the paper tray" or the "number of trays in the collator."
>
> You may list as many characteristics as you like, but 5-10 should suffice. If you need to make additional assumptions in order to answer the question, you will be given an opportunity to describe those assumptions at the end of the questionnaire.

For round 1, 29 IS managers and 23 business users responded, generating a total of 156 and 114 suggested characteristics, respectively. Thus, IS managers, on average, suggested 5.38 characteristics, versus 4.96 for business users.

The results of this round were pooled across the two samples, and the individual responses were independently categorised by two researchers. Initially, researcher 1 derived 18 categories, while researcher 2 derived 21 categories. After discussing the differences, the two researchers agreed on the 18 categories identified by researcher 1, as the difference between the two categorisations primarily reflected different levels of detail. Titles and descriptions of these categories of characteristics were written, where possible, using the words of respondents.

Characteristics Identified

The eighteen characteristics identified by the respondents are presented below. The order represents the overall frequency of mention of that characteristic in the round one responses of the IS managers.

1. Performance

The performance of a PC system is a key attribute as users don't want to wait for the machine to calculate results, retrieve data, or open application software. Performance is an emergent characteristic of the a number of components: CPU (generation, Level 1 cache, and clock speed), motherboard architecture (PCI versus ISA) and bus speed, quantity and type of Level 2 cache and RAM, type of drive interface (EIDE versus SCSI). Ideally, these components are purchased in an optimised configuration that eliminates any bottlenecks.

2. Compatibility with IT Architecture

It is important that PC systems be compatible with existing and planned systems and hardware in the organisation. Because network connectivity (see below) is important, PCs need to be able work with existing networks, hardware, and client/server applications. Again, to minimise support costs, it may be of interest to limit the number of PC configurations in the organisation; having many systems with the same video card, network card, etc., allows for a single PC image to be used.

3. RAM

While the quantity and type of RAM contributes to system performance, the quantity of RAM is also important in its own right as more RAM enables multitasking between multiple applications. Likewise, some software is very demanding of RAM and needs a large quantity in order to be installed or operate at an acceptable level of performance. Insufficient RAM is a common bottleneck to system performance.

4. Network Connectivity

The PC should have a network card and/or a modem for connecting to the LAN, WAN, or Internet. Network connectivity is necessary to support email, client/server applications, and sharing data across networks. In addition, some users may use the a modem to support telecommuting.

5. Industry Standard Components

Value can be derived from specifying high-quality, industry standard components such as network and video cards. If a standard component is chosen, it is more likely that drivers and technical support information will be available and supported in the future. In addition, if a problem arises (such as an incompatibility between a video card and an industry standard application package), it is likely that many others will have the same problem, and a solution will be available either from the hardware or software providers, or from discussion groups.

6. Operating System

The operating system is the primary determinant of the user interface of the PC, and thus affects the "user friendliness" or ease-of-use of systems. In addition, there is value to using the industry standard OS for availability of application software and compatibility with other systems in the organisation. In addition, the OS to a large extent determines the "stability" of PC systems, that is, their ability to run without crashing or freezing up.

7. Warranty and Service

The type and length of warranty are important because system downtime can be costly and inconvenient. On-site support is preferred, with local service being next-best. Having to ship systems to the manufacturer can be costly and time-consuming. In addition, technical support (over the telephone or Internet) that is oriented toward end-users is valuable.

8. Vendor

The vendor is a critical determinant of a number of characteristics of PC systems. The overall quality, reliability, and expected maintenance cost of systems are largely determined by the vendor's reliability rating. The overall stability of systems (the ability to run without "crashing") is partly determined by the vendor's level of certification of compatibility with hardware (e.g., network and video cards) and software (e.g., operating systems and network software). Likewise, certification for standards that allow for remote management of hardware over a network, such as DMI (Desktop Management Interface), are largely vendor-specific. Finally, choosing a reputable vendor that will exist in the future allows for planning an organisational IT architecture (discussed below) that includes a smaller number of vendors, thus reducing complexity and support costs.

9. Display Quality

The clarity of the monitor is an important concern in reducing eyestrain of users and making the overall system more ergonomic. Display quality is a function of the quality of both the monitor (dot pitch and refresh rate) and of the video card (which can also affect refresh rate).

10. Secondary Storage

The quantity of hard drive space determines the amount of software that can be installed as well as the quantity of data that can be stored locally. Since software continues to expand its use of this resource, it is important to "overbuy" for the future (i.e., buy a hard drive that is larger than needed to meet today's needs).

11. Ability to Upgrade

Because component prices continue to fall, it is important to purchase systems that can be upgraded in the future to extend their useful life. Thus, the motherboard should: have room to add additional RAM (without having to remove existing RAM); be able to handle the fastest processor available; and have free slots for adding additional hardware. Likewise the case should have free drive bays for adding additional hard drives; a tower case is probably best. Because the fastest processor on the market tends not to be priced competitively compared to the second or third-fastest clock speed, there exists a "sweet spot" just behind the technology curve that yields a better price/performance ratio. (For example, a 500 MHz Pentium-II CPU is currently more than twice as expensive as a 400 MHz Pentium-II CPU.) Buying a system that can be upgraded in the future allows for exploitation of the sweet spot.

12. External Drives

Drives with removable media, such as CD-ROM and floppy drives are important for installing software.

13. Price

PC system prices fluctuate due to promotions, discontinuations, etc., so it may be possible to get equivalent systems at different prices. However, lower prices generally come with a trade-off of lower quality components or a less reputable vendor (and hence a less stable and reliable system).

14. Monitor Size

A larger monitor can allow for larger text and less eye strain, or for higher resolutions and more "screen real-estate" for using multiple windows simultaneously. A large desktop prevents users from having to spend their time scrolling up-and-down and side-to-side.

15. High-Quality Input Devices

The keyboard and the mouse are the primary ways in which users interact with a system, and high-quality "ergonomic" devices are healthier and more pleasant for users. For example, the mouse should be smooth to move and sensitive to small hand motions so users don't waste time and physical energy. In addition, brand-name devices also tend to be more durable.

16. Backup Devices

Drives using either tape or disk-based media (e.g., ZIP, JAZ) allow users to backup their data.

17. Configured for Lifetime Use

A PC system should be configured with the latest components and processor to meet all anticipated demands during its lifetime. It is expensive to "visit" and modify a system, so this practice should be avoided where possible.

18. Multimedia Support

The availability of speakers, microphone, video hardware, and perhaps a DVD allow full multimedia support for editing sound, graphics, and video. Multimedia support is important for presentations and training applications.

Rating of Characteristics

For round two of the survey, the list of characteristics was fed back to the participants. Each participant was asked to rate the importance of each characteristic on a scale of 1-10 (with 1 being the least important). Following round 2, the average rating of each characteristic was calculated separately for IS managers and business users.

In round 3, participants were fed back their initial rating of each characteristic, along with the group's average rating of that characteristic. Participants were then asked to re-rate each of the characteristics. (The survey instruments for each round can be found in Appendix 2.) The ratings and rankings for each group, across rounds, are presented in Table 1 below.

Using the ratings supplied by each respondent, a set of rankings were derived. Kendall's Coefficient of Concordance (Kendall's W) is an indicator of the degree to which the respondents within groups agree on the relative rankings of the characteristics; Kendall's W will fall in the range 0-1. In the final round, Kendall's W for the IS managers is 0.515, which is considered a "moderate" level of agreement. For business users, the value is 0.726, indicating "strong" agreement.[57] Given that the purposes of this study were not to obtain a conclusive ranking of characteristics, but rather merely to generate the relevant set of characteristics, the decision was taken to end the survey after the third round, despite still-increasing levels of concordance. The Chi-squared values for the measures of concordance all display high levels of statistical significance, indicating that the rankings are not similar by chance. However, even moderate levels of agreement will produce extremely significant Chi-squared statistics provided that there are more than about ten raters.

[57] The classification of Kendall's W is taken from Schmidt (1997).

Table 1: Ranking of PC Characteristics

	IS Managers				Business Users			
	Round 2		Round 3		Round 2		Round 3	
	Rank	Rate	Rank	Rate	Rank	Rate	Rank	Rate
Performance	1	8.59	1	8.79	1	9.16	1	9.15
Compatibility	2	8.41	2	8.62	6	7.79	6	7.80
RAM	4	7.93	3	8.17	4	8.74	4	8.65
Network Connectivity	3	7.97	4	8.14	2	8.89	2	9.10
Industry Standard Components	6	7.38	5	7.69	8	7.16	10	7.00
Operating System	5	7.41	6	7.59	3	8.89	3	8.95
Warranty	9	7.14	7	7.38	9	7.11	11	6.75
Vendor	7	7.24	8	7.28	14	6.21	14	6.25
Display Quality	11	6.93	9	7.21	5	8.00	5	8.10
Secondary Storage	10	7.10	10	7.03	12	6.95	12	6.65
Ability to Upgrade	8	7.21	11	7.00	6	7.79	6	7.80
External Drives	12	6.86	12	6.83	10	7.05	8	7.05
Price	13	6.38	13	6.52	15	5.89	15	5.75
Monitor Size	14	6.21	14	6.48	10	7.05	8	7.05
High-quality Input Devices	16	5.72	15	5.76	13	6.26	12	6.65
Backup Devices	15	5.76	16	5.59	16	5.68	16	5.40
Lifetime Use	17	5.62	17	5.55	17	5.37	17	5.35
Multimedia	18	5.24	18	5.00	18	5.00	18	5.20
Sample Size	29		29		19		20	
Kendall's W	0.294		0.515		0.392		0.726	
Chi-square	144.877		253.852		126.741		246.774	
Statistical Significance	p < 0.0001		p < 0.0001		p < 0.0001		p < 0.0001	

The ratings from the two groups show a moderate degree of consistency. For example, examining the top five characteristics from each group shows that three characteristics appear on both lists (performance, network connectivity, and RAM). The differences between the two groups were explored using both parametric approaches (t-tests of ratings) and non-parametric approaches (Mann-Whitney U test of rankings). Both approaches produced an identical list of characteristics that showed statistically significant differences (at the 5% level). The results of the t-tests are presented in Table 2 below.

Table 2: Differences between IS Managers and Business Users

Characteristic	t-statistic	More important to:
Performance	1.59	-
Compatibility	-3.66 ***	IS Managers
RAM	2.10 *	Business Users
Network Connectivity	3.62 ***	Business Users
Industry Standard Components	-2.15 *	IS Managers
Operating System	4.11 ***	Business Users
Warranty	-1.94	-
Vendor	-3.08 **	IS Managers
Display Quality	2.96 **	Business Users
Secondary Storage	-1.12	-
Ability to Upgrade	2.81 **	Business Users
External Drives	0.68	-
Price	-1.90	-
Monitor Size	1.53	-
High-quality Input Devices	2.19 *	Business Users
Backup Devices	-0.41	-
Lifetime Use	-0.55	-
Multimedia	0.45	-

* indicates significance at the 0.05 level
** indicates significance at the 0.01 level
*** indicates significance at the 0.001 level

Some of these differences accord with the stereotypical tensions between IS managers and end-users. IS people are more concerned with overall compatibility of IT architecture, enforcing standards, and having some control over the choice of vendor. In the rationale and comments on these characteristics, CIPS members frequently cited the positive benefits of standard PC configurations and using a limited number of vendors in terms of reducing administration and support costs. Users, not surprisingly, were more concerned with the interface of PC systems, including high-quality input devices, high-quality displays, and the latest generation of operating system. (Monitor size was also more highly valued by business users, and was statistically significant at the 10% level.) In their descriptions and comments, business users cited the importance of having an "ergonomic" workstation with a large, clear display that reduced fatigue and eye strain in addition to enhancing productivity through use of multiple windows simultaneously.

Interestingly, business users also rated network connectivity, RAM, and ability to upgrade more highly than did CIPS members. Many business users viewed uninterrupted, high-bandwidth network access to be critical to working effectively. In their comments regarding upgrades and RAM, it is clear that business users value having systems that are at or are at least near the current standard of performance. However, users acknowledge that it is much easier to get approval for an upgrade of, say, $750 for more RAM and a new hard drive than it is to justify the purchase of an entire new system. Among the business users in this sample, at least, there was sufficient technical savvy to identify and exploit opportunities for low-cost upgrades. In contrast, CIPS members stressed more highly the need to avoid "visiting" and modifying a system during its service life due to the costs associated with the visit and supporting multiple configurations within the organisation.

Summary

The two Delphi surveys described above provide a snapshot of the important PC characteristics from a business perspective in 1999. This list of characteristics provides an important input to specifying the hedonic function for PCs. Particularly, it gives external validation for the common practice of focussing on the performance of microcomputers. However, the limitations of this list must be recognised, particularly as it relates to constructing a price index. The list produced in 1999 reflects the use of PC systems at the close of the 20th century, and incorporates the effects of a number of technological innovations that have driven business practice. As recently as the early 1990s, for example, PCs tended to be used in "stand-alone mode" i.e., not as part of a network. Likewise, multimedia and CD-ROMs were little used in the business environment. Thus, care must be taken not to over-weight the importance of recent innovations in determining an appropriate hedonic function for computers.

Chapter 4: Laptop Price Indexes

This chapter uses two methods to construct price indexes for laptop PCs. As part of this work, two distinct approaches to measuring performance are developed and compared. The first approach, dubbed "technical proxies," uses only technical attributes of laptop systems as independent variables in the hedonic function. The second, "benchmark" approach uses a direct measure of system performance, as well as technical attributes, as independent variables.

Data

The need for reliable and unbiased benchmark test results considerably constrained the choice of data sources. Thus, as with Baker (1997), data were drawn from annual reviews of laptop PCs published in *PC Magazine*. In this case, the period of coverage is 1990-1998. A summary of the variables is presented in Table 3, and selected means are presented in Table 4 and in Table 5. This sample reflects the removal of a small number of observations, judged to be sufficiently different from typical laptop PCs to be a different class of machines.[58]

The means of a number of variables increase by one (e.g., RAM, Mspeed) or two (e.g., HD, Proc) orders of magnitude in this nine-year period, reflecting the rapid rate of quality change embodied in the systems. On the other hand, the battery life index remains almost constant over the time period.[59] However, given the increased power demands resulting from the shift to power-hungry colour screens, the increase in screen size, resolution, and brightness, and the inclusion of ever more powerful CPUs, the maintenance of constant battery life reflects considerable innovation. In addition to the battery life index, dummy variables are included for nickel-metal hydride (Nihyd) and lithium-ion (Lithium) batteries (the default battery technology is nickel-cadmium), because these types of batteries not only provided more power, but did it in a lighter package that recharges more quickly.

The Discount dummy variable captures all prices that are not list prices, including mail-order prices and estimated street prices (as categorised by *PC Magazine*). The Major dummy variable includes brands that have 15 or more observations in the data set, but excludes direct retailers (i.e., Dell and Gateway). The Major dummy includes the brands Compaq, DEC, IBM, Texas Instruments, Toshiba, NEC, and Zenith.

---

[58] The outliers include the 1992 BCC SL007 which is the only machine to feature an encrypted hard drive (presumably the source of the James Bond numbering); the 1993 Compaq Contura 4/25 which was eliminated due to incomplete information; the 1993 Grid Convertible, the only pen-based computing platform; and a number of "luggable" machines presented in 1992 that do not have battery power, weigh in the neighbourhood of 20 lbs., and are thus not considered laptops.

[59] This index is composed of measured times to exhaust the battery under a full-usage scenario, and thus likely underestimates battery life under more typical usage. With the exception of 1994 data (which was estimated from the results of a related test), these measures are taken directly from *PC Magazine* test reports.

Table 3: Description of Laptop Variables

Variable	Description	Expected Effect
Lprice	Log of price	N/A
Disc	Dummy variable for discount price	-
Lbat	Log of battery life index (minutes)	+
Lproc	Log of processor performance index	+
Lhdsize	Log of hard disk size (megabytes)	+
LRAM	Log of random access memory (megabytes)	+
Colour	Dummy variable for colour screen	+
Lpix	Log of number of pixels in maximum resolution	+
Ldiag	Log of diagonal measure of screen size (inches)	+
Active	Dummy variable for active matrix LCD technology	+
Passive	Dummy variable for passive matrix LCD technology	+
Lmspeed	Log of internal modem maximum speed (bps)	+
Lcdspeed	Log of maximum CD-ROM speed	+
Major	Dummy variable for major brand	+
Lithium	Dummy variable for lithium-ion battery	+
Nihyd	Dummy variable for nickel-hydride battery	+
Lweight	Log of weight (pounds)	-
Ldense	Log of density (pounds per cubic inch)	+
Intel	Dummy variable for Intel CPU	+
D286	Dummy variable for 286 CPU	+
D386	Dummy variable for 386 CPU	+
D486	Dummy variable for 486 CPU	+
D586	Dummy variable for Pentium CPU	+
D786	Dummy variable for Pentium-II CPU	+
DK6	Dummy variable for K6 CPU	+
LMHz	Log of processor clock speed in MHz	+
LMHz286	LMHz * D286 interaction term	+
LMHz386	LMHz * D386 interaction term	+
LMHz486	LMHz * D486 interaction term	+
LMHz586	LMHz * D586 interaction term	+
LMHz786	LMHz * D786 interaction term	+
LMHzK6	LMHz * DK6 interaction term	+
LL1Cache	Log of level 1 (on chip) cache memory (kilobytes)	+
LL2Cache	Log of level 2 cache memory (kilobytes)	+

Table 4: Means of Selected Laptop Variables

Year	n	Price	Colour	Wgt	RAM	HD	Major	Mspeed	Act	Pass	CD	Bat	Lith	Nihyd
1990	14	$5,700.93	0	11.6	2.3	36	0.43	2400.0	0	0	0	130.3	0	0
1991	27	$3,676.93	0	6.9	2.4	29	0.15	2311.1	0	0	0	130.4	0	0.04
1992	68	$3,315.06	0.07	6.8	4.0	84	0.20	3070.6	0.04	0.03	0	149.3	0	0.04
1993	63	$3,026.40	0.43	6.4	4.4	138	0.38	6476.2	0.24	0.76	0	143.8	0	0.21
1994	70	$3,475.27	0.73	6.5	9.0	270	0.27	13028.6	0.36	0.60	0	141.5	0	0.40
1995	80	$3,935.15	1.00	6.8	14.8	549	0.19	6480.0	0.58	0.42	0.22	120.8	0.08	0.91
1996	58	$3,874.52	1.00	7.0	16.0	1034	0.22	28055.2	0.78	0.22	3.10	131.4	0.46	0.53
1997	59	$3,881.14	1.00	7.2	25.5	2051	0.15	33420.3	0.92	0.08	9.06	138.0	0.78	0.22
1998	53	$2,999.60	1.00	7.3	47.1	3700	0.24	38011.3	0.89	0.11	21.51	175.2	0.87	0.13

Table 5: Means of Laptop Performance Variables

Year	MHz	Proc	L1 Cache	L2 Cache	286	386	486	586	786	K6
1990	15.4	8.6	0	0	4	12	0	0	0	0
1991	17.9	10.3	0	0	0	27	0	0	0	0
1992	23.1	15.9	0.8	12.6	0	61	7	0	0	0
1993	30.4	29.2	6.1	16.1	0	15	48	0	0	0
1994	49.4	45.2	8.0	3.6	0	0	70	0	0	0
1995	82.0	90.5	10.2	78.4	0	0	58	22	0	0
1996	117.2	183.6	16.0	216.3	0	0	0	58	0	0
1997	164.9	291.7	27.7	286.4	0	0	0	59	0	0
1998	249.2	529.8	33.8	492.7	0	0	0	30	20	3

This data set reflects a rapid pace of technological change, in that almost no models appear in more than one period. This fact obviates the need to explore the issues surrounding the Age and Vintage of models, as over 95% of models are of Age zero.

Likewise, the relatively small size of the data set does not permit exploration of issues surrounding technology pricing and capabilities. An attempt was made to produce a "Latest Technology" dummy variable to reflect whether a model used the highest available generation and clock speed of processor. However, the small sample size means that very few models (and in several years, zero models) embodied the latest technology. Thus, this variable was dropped from the analysis.

Approach One: Technical Proxies for Performance

The technical proxies approach follows the tradition of hedonic functions for constructing price indexes for computer components. In this method, a number of the dozens of attributes of microcomputer systems must be identified as the sources of user value and selected as regressors. The challenge is to distinguish the attributes that directly or indirectly provide utility to computer users from the purely technical attributes that are not important from a user's point of view. The perfect list would be comprised of all attributes, and only attributes, that contribute to sources of user value. In this study, the choice of technical attributes is guided both by the results of the Delphi Survey discussed in Chapter 3, as well as the author's own experience with the sources of user value in laptop systems.

The results of this analysis will be a specification that accords closely with the accumulated empirical work on computer components. The variables included are technical attributes and should not be subject to significant measurement error; neither do these variables require interpretation or judgement in their construction. Because the specification need not include any attributes of the operating system or applications software, it will produce a "pure hardware" index, measuring the rate of quality-adjusted price decline of laptop "boxes."

Modelling Performance

Comprehensive modelling of system performance is more the ken of engineering than economics, but accounting for quality change necessitates at least some operationalisation of performance in a hedonic function. At the risk of oversimplification, the performance of a microcomputer will depend upon the following factors: (listed, according to the opinion of the author, in order of decreasing importance)

- The architecture of the CPU, i.e., its generation (e.g., Pentium)
- The clock speed of the CPU
- The quantities of Level 1 and Level 2 cache memories
- The architecture, chip set, and bus speed of the motherboard
- The quantity and access speed of primary storage (RAM)
- Additional CPU specifications (e.g., MMX, SX, DX, etc.)
- The speed of the secondary storage subsystem, which depends on the interface, disk seek time and transfer rates
- The speed of the graphics subsystem, which depends on the supporting chipset, quantity and type of video RAM, and acceleration features.

Prior work on microcomputer price indexes has typically included a dummy variable for the architecture of the CPU as well as a measure of clock speed in MHz (Berndt and Griliches, 1990; Nelson et al., 1994; Berndt et al., 1995), although some have used only clock speed (Baker, 1997).

However, such an operationalisation constrains the hedonic function to treat a MHz as an homogeneous "good" across different CPUs. Given the radically different makeup of even subsequent generations of CPUs in the same family, the implicit assumption underlying this constraint is clearly not satisfied. For example, a 386DX CPU contained 275,000 transistors, versus approximately 7.5 million transistors in a Pentium-II CPU. The Pentium-II has a number of features (longer word length, parallel execution, large on-chip cache) that enable it to do much more processing, per clock cycle, than can any earlier Intel CPU.[60]

Thus, the physical design of chips suggests that an interaction term between the dummy variable for the generation of CPU and the clock speed of the CPU in MHz will provide a good first-order approximation of the processing capabilities of the CPU. To date, none of the empirical work on microcomputers has included such a CPU-by-MHz interaction term in the hedonic specification.

Including the quantities of cache memory and RAM in the hedonic function is straightforward, and justified in that more cache memory or more RAM will improve processing performance through faster access to data and instructions. In addition, since the advent of multi-tasking operating systems (with the release of Windows 3.0 in

[60] See chapter 4 in Williams, Sawyer, and Hutchinson (1999) for an excellent discussion of microprocessors.

1990), RAM is also a direct source of user value in enabling switching between applications.

Data on the architecture of the motherboard in PC systems are difficult to acquire in the requisite detail, but this architecture is, by physical necessity, almost entirely dictated by the generation and speed of the CPU.

Likewise, the speed of the secondary storage is largely determined by the type of interface (e.g., IDE versus SCSI), the amount of software cache utilised, and the speed of the hard disk. Again, detailed data on this subsystem can be difficult to acquire. Over time, the speed of hard disks has been very highly correlated with the size of disks. Thus, in addition to its direct utility by providing storage space, hard drive size also indirectly captures user value through its association with system performance.

Finally, it is difficult to acquire detailed data regarding the determinants of graphics system performance. However, a reasonable proxy may be to simply use the maximum resolution supported, measured either in terms of the number of pixels or, less directly, by the quantity of video RAM. These proxies are equivalent for most intents and purposes due to the tight correlation between video RAM and resolution. Over time, overall video performance has been correlated with resolution, thus making resolution both a direct and indirect measure of user value.

In summary, it should be possible to reasonably model the performance of a microcomputer in a hedonic function using the following attributes: CPU*MHz interaction term, cache and primary memory size, hard disk size, and maximum resolution.

Approach Two: Benchmark Measures of Performance

The benchmark approach uses direct measures of system performance, as measured by Ziff-Davis Benchmark Operations and published in PC Magazine. Conducting any system benchmark test requires that an operating system be installed on the computer. Thus, performance measurement is not a pure measure of hardware performance, but of the interaction between hardware and operating system. Therefore, the unit of analysis becomes "microcomputer plus operating system."

Using a single benchmark to measure system performance replaces numerous technical proxies for performance, resulting in a more parsimonious specification of the hedonic function. This specification is more closely aligned with the theoretical underpinnings of the hedonic approach, as the performance measure is directly interpretable as a source of user-value, per Triplett's prescription. In addition, this approach may arrive at a significantly different estimate of the rate of quality change than the technical method of the previous section because it accounts for two sources of performance change that the technical specification does not: the interaction of the computer hardware and the operating system software, and the non-linear aggregation of the performance of individual hardware components to produce system performance.

Constructing Performance Benchmarks

The chief difficulty with using benchmarks for hedonic analyses is obtaining a set of benchmarks that are expressed in comparable units over time. Typically, labs that tested microcomputers changed their benchmark tests to reflect changes in the usage of systems over time. Benchmark tests, especially applications benchmarks, tended to be revised on an annual basis.

However, one series of benchmarks published by Ziff-Davis has remained relatively stable over time. This series of processor performance measures covers the period 1990-1998, encompassing six versions and five different measurement scales. In order to make these scores comparable over time, the results were translated to a common scale.

To determine the relationship between adjacent versions of the processor benchmark, two approaches were taken. First, where available, differences introduced by design (such as scaling the benchmark with respect to a base machine) were taken into account on the basis of communication with Ziff-Davis Benchmark Operations.[61] Second, the published data were examined for "matches," that is, machines that were tested under two versions of the benchmark. These matches allowed for scaling between the units of the two results.

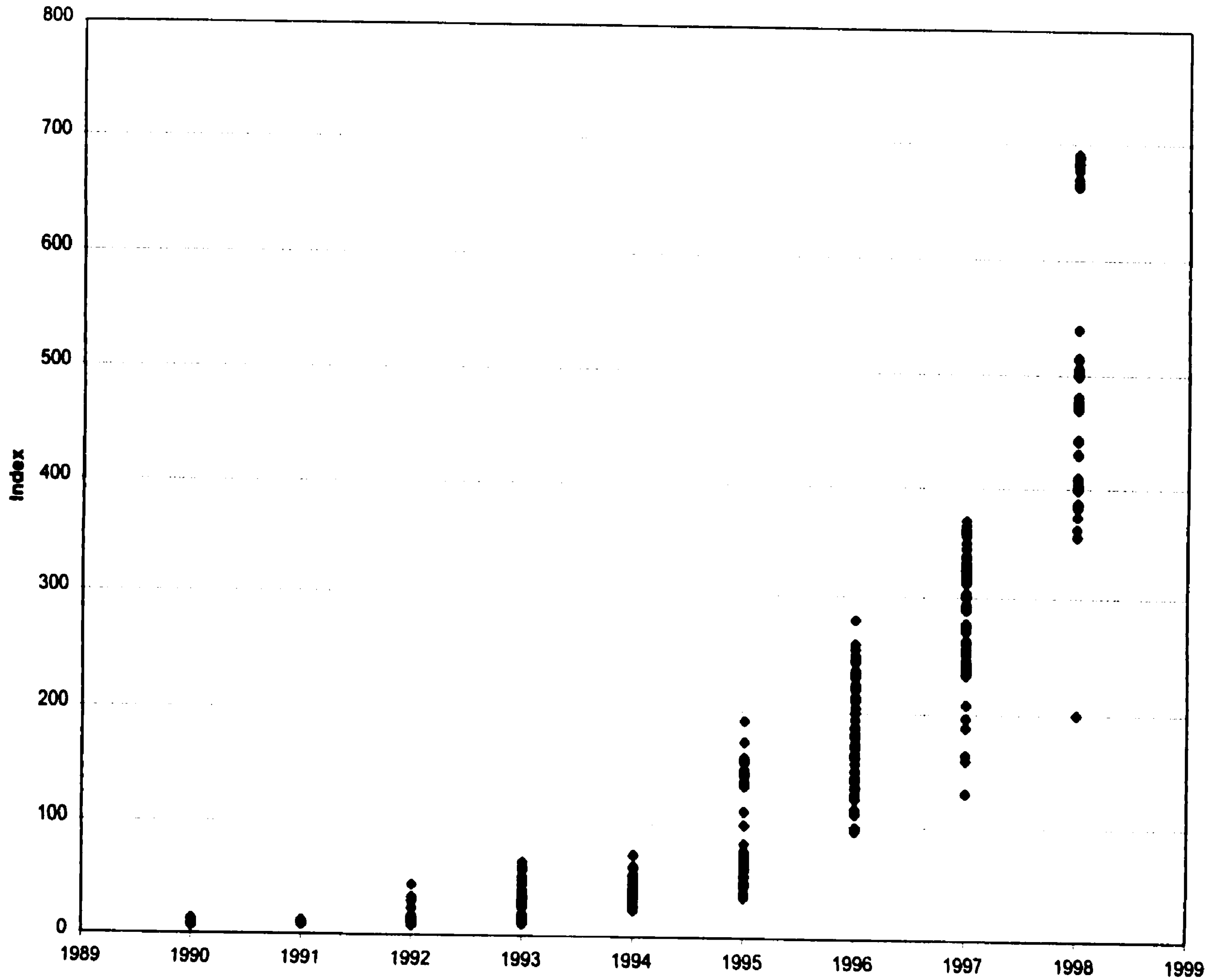
Using this scaling procedure produced index values for all models in the data set, which are depicted in Figure 3. An exponential trend line fit to the data indicates that in this sample, performance was doubling approximately every 14.5 months, slightly more rapidly than one would expect extrapolating from Moore's Law. By all accounts, Moore's Law appears to continue to (at least approximately) hold, in that the number of transistors on microchips has continued to double every 18 months. Thus, as one would expect, performance does not appear to be linearly related to the number of transistors on the CPU, as other factors (especially CPU clock speed and bus width and speed) also affect performance.

The processor benchmarks underlying this index were designed to assess only the computational performance of the computer system. As such, they do not take graphics or input/output to secondary storage into account. Also, these tests are reported to be largely independent of RAM (unlike application benchmarks). Thus, this index reflects the computational performance of the combination of CPU, cache memories, motherboard architecture, and operating system software.

---

[61] Private communication with Jennie Faries, 1999.

Figure 3: Laptop Processor Index



Benchmark Specifications

The form of the hedonic function, as established out by Rosen, is an empirical question. Within this data set, the double-log specification was preferred over linear or semi-log specifications. A Box-Cox test confirms this choice (λ = -0.0102, and the 95% confidence interval ranges from -0.1738 to 0.1634). While recent work has asserted that in a competitive market, the correct specification of the hedonic function is linear (Arguea and Hsiao, 1993), the choice of functional form generally has little effect on estimated price indexes.[62]

Given the likely presence of heteroskedasticity, all standard errors and hypothesis tests are computed using the White heteroskedasticity-robust procedure. The results of the pooled specification are presented in Table 6. All coefficients display the predicted sign, and the majority are statistically significant. The processor index is significant at the $p < 0.001$ level, and the battery life index is significant at the 0.05 level. Major sources of user value appear to be related to performance (Lproc, Lhdsize, LRAM, Lmspeed, Lcdspeed), portability and battery life (Lbat, Lithium, Lweight), and the display (Colour, Lpix, Ldiag, Active). While the active matrix displays commanded a significant price premium, the coefficient on the passive matrix dummy variable was positive but non-significant, indicating that passive matrix LCD screens did not command a significant premium over the older LCD technology. Likewise, the nickel hydride battery did not command a premium over the older nickel cadmium technology. Finally, while the coefficient for weight was significant and negative, indicating that buyers paid a price premium for lighter machines, *ceteris paribus,* the coefficient for density was non-significant, indicating that buyers were less concerned with density or volume.[63] Finally, the time dummy variables indicate a quite rapid rate of price decline; applying the dummy variable technique, one finds the AAGR in quality adjusted prices to be -39.6% over the period 1990-1998.

Following Berndt and Griliches (1990) and Nelson et al., (1994), an interaction specification was developed. Interaction terms were constructed between a time counter variable and the numerical variables displaying a trend in the linear specification. The time counter variable is set to zero in 1990, and increases by one in each subsequent year. Interaction variables were created with each of: Lbat, Lproc, Lhdsize, LRAM, Lpix, Ldiag, Lmspeed, Lcdspeed, and Lweight. However, an F-test failed to reject the null hypothesis that the coefficients for all of Lbat, Lproc, Lhdsize, LRAM, Lpix, Ldiag, and Lweight were equal to zero. The only significant interaction terms were Time*Lmspeed and Time*Lcdspeed. The results of the model with these two interaction terms are also presented in Table 6.

---

[62] Hoffmann (1998) remarks "...the question of correct functional form seems, if anything, to be a problem to which too much importance is attached." p. 60.

[63] The variable for volume could not be included with weight and density in the double-log specification due to perfect collinearity.

Table 6: Laptop Pooled Benchmark Specifications

	Linear Model		Interactions Model	
Variable	Coefficient	t-statistic	Coefficient	t-statistic
Disc	-0.1247	-3.49 ***	-0.1177	-3.38 ***
Lbat	0.0581	1.97 *	0.0621	2.11 *
Lproc	0.1363	4.37 ***	0.1367	4.54 ***
Lhdsize	0.2233	7.52 ***	0.2234	7.57 ***
LRAM	0.2052	5.98 ***	0.1984	5.78 ***
Colour	0.3087	8.52 ***	0.3061	8.56 ***
Lpix	0.1421	1.96 *	0.1576	2.09 *
Ldiag	0.7633	4.66 ***	0.7325	4.58 ***
Active	0.2896	5.16 ***	0.2905	5.28 ***
Passive	0.0500	1.00	0.0538	1.10
Lmspeed	0.0098	3.39 ***	0.0397	5.21 ***
Lcdspeed	0.0644	2.11 **	0.4605	3.10 **
Major	0.2324	11.77 ***	0.2286	11.59 ***
Lithium	0.1255	3.22 ***	0.1366	3.49 ***
Nihyd	0.0436	1.71	0.0532	2.11 *
Lweight	-0.1514	-2.13 *	-0.1483	-2.07 *
Ldense	0.0512	0.79	0.0383	0.60
Intel	0.0775	2.00 *	0.0756	1.99 *
D91	-0.3711	-4.06 ***	-0.3289	-3.58 ***
D92	-1.0371	-10.63 ***	-0.9535	-9.47 ***
D93	-1.5629	-12.92 ***	-1.4483	-11.57 ***
D94	-1.9231	-15.16 ***	-1.7776	-13.25 ***
D95	-2.3305	-15.22 ***	-2.1323	-13.07 ***
D96	-2.7937	-16.26 ***	-2.5991	-14.04 ***
D97	-3.3155	-17.15 ***	-2.9556	-14.64 ***
D98	-4.0596	-18.16 ***	-3.4609	-15.00 ***
Constant	3.8948	4.47 ***	3.4717	3.80 ***
Time*Lmspeed			-0.0050	-3.85 ***
Time*Lcdspeed			-0.0614	-2.75 **
R^2	0.7490		0.7571	
N	492		492	
Root MSE	0.1806		0.1776	

* significant at the 0.05 level
** significant at the 0.01 level
*** significant at the 0.001 level

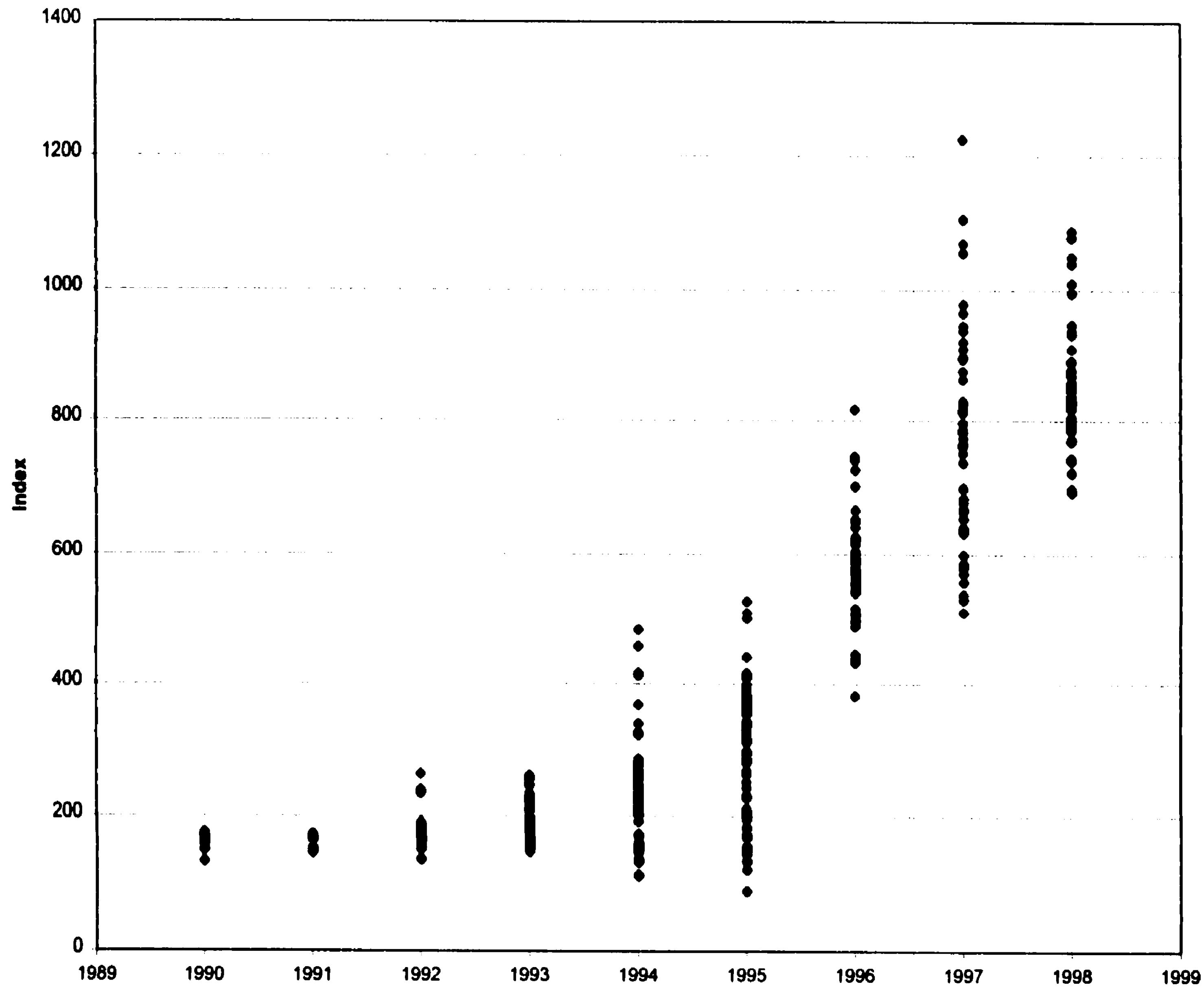
The coefficients on both of the interaction terms are negative, indicating that the price of modem speed and CD-ROM speed both decline over time in the sample. The interactions model presents a modest increase in explanatory power (root MSE is reduced by 1.7%), and generally minor changes in the estimated coefficients. Only one coefficient changes significance level, with the dummy variable for nickel-hydride batteries becoming significant at the 0.05 level. Other than Lmspeed and Lcdspeed, the coefficients displaying the largest changes are the time dummy variables, all of which are smaller (in absolute terms) with the addition of the time interaction terms. Applying the dummy variable technique, the resulting AAGR is -39.9%, not substantial different from the model without time interactions.

The finding that there is no significant interaction term with any of RAM, hard disk size, or the performance index is somewhat unexpected, given that the means of these variables increase from one to two orders of magnitude across the sample. The implied stability of the implicit prices of these attributes over time suggests that these characteristics have been evolving at approximately the same rate, in terms of price/performance, and that this rate is adequately captured by the time dummy variables in the pooled specifications.

One further performance index was constructed and tested in the hedonic function. Using techniques similar to those described for the processor benchmark above, an index was constructed that measured hard disk throughput. As with the processor index, this index was expressed in common units across the sample timeframe. This index (see Figure 4) displayed steady improvement, with a doubling of throughput approximately every 31.5 months. Although highly correlated with the processor index across the entire sample (0.91), the correlation within years was much lower, suggesting that it was picking up an aspect of performance reasonably orthogonal to processor performance. However, when included in the pooled specification of the hedonic function, the estimated coefficient is non-significant (coefficient value is -0.01215, t-statistic -0.261). This result suggests that if hard disk performance is a source of user value in laptops, it apparently does not command a price premium. The inclusion of the disk index did not substantially affect the estimated coefficients of either the processor index or the major brand dummy variables, suggesting that neither of these were serving as proxies for disk performance.[64]

[64] The estimated coefficients for the processor index changed from 0.1622 to 0.1657 with the inclusion of the disk index; likewise, for the major dummy, the figures are 0.2360 and 0.2357.

Figure 4: Laptop Hard Disk Throughput Index



Equivalence of Benchmark and Proxies

To test the assertion that microcomputer performance could be adequately modelled by the technical proxies suggested above, these proxies were regressed on the performance index. The results of this exercise are presented in Table 7. Dummy variables for generations of processors were not included in order to constrain the effects of MHz (within generations) to be comparable across generations.

Table 7: Proxies Regressed on Laptop Processor Index

Variable	Coefficient	t-statistic
LL1cache	0.2808	5.46 ***
LL2cache	0.0429	7.51 ***
LMHz286	0.5180	8.28 ***
LMHz386	0.6265	13.76 ***
LMHz486	0.6643	21.32 ***
LMHz586	0.7602	23.95 ***
LMHz786	0.8300	25.06 ***
LMHzK6	0.7513	19.39 ***
LRAM	0.0369	1.43
Constant	0.4959	3.99 ***
R^2	0.9819	
N	492	
Root MSE	0.1757	

*** significant at the 0.001 level

The model fit is good, displaying a high R^2 (0.98), with all of the CPU-by-MHz coefficients having the expected sign and statistical significance. A Box-Cox test failed to reject the double-log specification, though the results are similar with a semi-log or linear specification, indicating that the relationship between the proxies and performance is quite robust. Further, the coefficients display the expected ranking, showing that, *ceteris paribus,* a MHz of clock speed from a 286 processor produces less performance than a MHz from a 386, a 386 less than a 486, and so on. Likewise, the coefficients on the L1 and L2 cache memories display the expected ranking, with a kilobyte of L1 cache having approximately 7 times the effect on Lproc of a kilobyte of L2 Cache.[65] The relative magnitude of these coefficients indicates that doubling the quantity of L1 cache leads to a 21% increase in performance, versus a 3% increase in performance for each doubling of L2 cache. Finally, RAM is not a statistically significant contributor to the

[65] L1 cache is the fastest, most expensive form of primary storage and is physically located on the same chip as the CPU. L2 cache is located just off the CPU, and is typically linked to the CPU via a special bus giving higher access rates. Both L1 and L2 cache are much faster than RAM, which provides the bulk of primary storage. Typically, a machine is configured with an order of magnitude more L2 cache than L1 cache, and approximately 2-3 orders of magnitude more RAM than L2 cache in an attempt to optimize performance.

processor index, confirming the assertion that the Ziff-Davis processor benchmarks are largely RAM-insensitive.

Thus, the processor index has been shown to be an adequate summary measure of performance that spans the same space as the technical proxies for performance. In addition, the use of a single summary measure for performance allows for a more parsimonious specification of the hedonic function, in line with the use of MIPS measures in the study of mainframe processors.

Technical Proxies Specification

The results of an alternative specification using technical proxies, rather than the performance index, are presented in Table 9. The interactions model was developed in the same manner as for the benchmark specification; once again, only the time by Lmspeed and Lcdspeed interaction terms emerged as statistically significant. Several points are worth noting. First, the indexes produced by these specifications closely approximate those using the performance index: the AAGR's for the proxy specification are -39.2% and -39.6% (without and with interaction terms, respectively), versus -39.6% and -39.9% for the benchmark specifications. Second, the estimated coefficients for the variables common to both specifications retain the same sign, approximate magnitude, and approximate degree of statistical significance. These first two findings confirm that the two approaches are largely equivalent in terms of producing price indexes. Third, for the coefficients on the CPU-by-MHz proxies that are statistically significant, the estimates display the same relative ranking as those in the regression of the proxies on the index, presented in Table 7. This result is further confirmation that the processor index aggregates the technical proxies in an economically meaningful manner. Alternately, the equivalence of these approaches can be taken as evidence that this set of technical proxies serves as an adequate measure of performance, and could thus be applied in larger data sets for which direct performance measures are not available.

Table 8: Laptop Technical Specifications

	Linear Model		Interactions Model	
Variable	Coefficient	t-statistic	Coefficient	t-statistic
Disc	-0.1205	-3.37 ***	-0.1122	-3.21 ***
Lbat	0.0764	2.63 **	0.0809	2.76 **
LL2cache	0.0229	3.20 ***	0.0190	2.70 **
LMHz286	0.0717	1.01	0.0785	1.10
LMHz386	0.0424	0.92	0.0411	0.90
LMHz486	0.0903	2.08 *	0.0872	2.03
LMHz586	0.1025	2.28 *	0.1065	2.42 *
LMHz786	0.1310	2.84 **	0.1359	3.03 **
LMHzK6	0.1131	2.42 *	0.1258	2.77 **
Lhdsize	0.2121	6.51 ***	0.2136	6.61 ***
LRAM	0.1977	5.80 ***	0.1892	5.56 ***
Colour	0.3238	8.95 ***	0.3209	8.96 ***
Lpix	0.1599	2.29 *	0.1825	2.56 **
Ldiag	0.7413	4.57 ***	0.7214	4.54 ***
Active	0.2585	4.47 ***	0.2630	4.63 ***
Passive	0.0268	0.52	0.0354	0.70
Lmspeed	0.0098	3.39 ***	0.0383	5.00 ***
Lcdspeed	0.0481	1.54	0.4632	3.07 **
Major	0.2353	11.71 ***	0.2284	11.37 ***
Lithium	0.1285	3.28 ***	0.1389	3.55 ***
Nihyd	0.0488	1.91	0.0571	2.27 *
Lweight	-0.1189	-1.46	-0.1160	-1.41
Ldense	0.0690	1.04	0.0546	0.84
Intel	0.0812	2.05 *	0.0864	2.21 *
D91	-0.3263	-2.78 ***	-0.2812	-2.38 **
D92	-0.9710	-7.83 ***	-0.8803	-6.96 ***
D93	-1.5130	-10.29 ***	-1.3926	-9.20 ***
D94	-1.8584	-12.11 ***	-1.7092	-10.66 ***
D95	-2.2791	-13.45 ***	-2.0852	-11.58 ***
D96	-2.7489	-14.52 ***	-2.5786	-12.65 ***
D97	-3.2338	-15.39 ***	-2.8982	-12.83 ***
D98	-4.0021	-17.10 ***	-3.4260	-13.47 ***
Constant	3.8125	4.11 ***	3.2682	3.43 ***
Time*Lmspeed			-0.0047	-3.67 ***
Time*Lcdspeed			-0.0640	-2.80 **
R^2	0.7550		0.7626	
N	492		492	
Root MSE	0.1784		0.1756	

* significant at the 0.05 level
** significant at the 0.01 level
*** significant at the 0.001 level

Technological Regime Specification

Examining the sample means in Table 2, one can see three distinct technological regimes, corresponding roughly to display technology. In the period 1990-1991, all of the machines used monochrome displays, non-enhanced LCD technology, and the vast majority (98%) used nickel-cadmium batteries. The period 1992-1994 saw the transition to colour displays, the adoption of active- and passive-matrix enhancements to LCD, and growth in the use of nickel-hydride batteries. Finally, the period 1995-1998 features entirely colour displays, all of which are enhanced LCD (either active or passive matrix), the appearance of CD-ROM drives, and the complete disappearance of nickel-cadmium batteries in favour of either nickel-metal hydride or, later, lithium ion.

To some extent, the sharp delineations between these eras reflects the selection procedures chosen by the editors of *PC Magazine*. The machines selected for review were not necessarily a representative sample, and for some years explicit selection criteria were used (e.g., 386 CPUs in 1991, colour displays in 1995, and Pentium CPUs in 1996), introducing a source of potential bias. Nevertheless, the laptop has gone through distinct periods in which technical improvements were concentrated toward different objectives. The three distinct technological eras described above are estimated separately, with the results presented in Table 7.

Adjacent Year Specification

The sample was split into pairs of adjacent years, and then the standard F-test was used to see if additional years would pool with the adjacent years. Using this methodology, the timeframes 1990-94, 1994-97, and 1997-98 emerged as distinct. The results of the hedonic model run on these timeframes are presented in Table 8.

It should be noted, however, that for the reasons discussed in the technological regime section above, the standard F-test method is less meaningful as attributes appear and drop out across years. Thus, this approach is presented strictly for comparison to prior research.

Resulting Price Indexes

Price indexes were constructed using all four specifications of the hedonic function and applying the dummy variable approach.[66] The resulting indexes and average annual growth rates (AAGR) are presented in Table 9. For the models involving the time interaction terms, the log change in price is computed using the average component values across periods t and $t+1$, as in Berndt and Griliches (1990) and Baker (1997).

---

[66] For all calculations of indexes using the dummy variable approach, the standard correction factor of one-half the squared standard error of the estimated coefficient has been added.

Table 9: Laptop Technological Regimes

	B&W: 1990-91			Mixed: 1992-94			Colour: 1995-1998		
Variable	Coefficient	t-statistic		Coefficient	t-statistic		Coefficient	t-statistic	
Disc	-0.1613	-1.34		-0.2241	-4.38	***	-0.0508	-1.21	
Lbat	0.2108	0.81		-0.0023	-0.03		0.0837	2.59	**
Lproc	0.1087	0.52		0.1232	2.51	**	0.1336	3.28	***
Lhdsize	0.1420	1.26		0.2272	5.02	***	0.2450	5.73	***
LRAM	0.2762	1.34		0.0839	1.26		0.2574	6.42	***
Colour				0.2719	6.21	***			
Lpix	0.2361	1.07		0.1659	1.42		0.1309	1.42	
Ldiag	0.7771	1.11		0.3901	1.65		1.0265	4.36	***
Active				0.3085	4.98	***	0.2140	7.53	***
Passive				0.0442	0.94				
Lmspeed	0.0476	3.68	***	0.0355	6.60	***	0.0053	1.80	
Lcdspeed							0.0626	2.06	*
Major	0.2609	3.22	**	0.2394	7.21	***	0.2143	7.96	***
Lithium							0.0668	2.31	*
Nihyd				0.0641	2.34	*			
Lweight	-0.2274	-0.93		-0.1254	-0.84		-0.1867	-1.74	
Ldense	0.2696	0.85		-0.1025	-1.04		0.1090	1.30	
Intel				0.0876	1.80		0.0005	0.01	
D91	-0.4654	-1.83	*						
D92									
D93				-0.5094	-10.15	***			
D94				-0.8107	-11.27	***			
D95									
D96							-0.5183	-7.79	***
D97							-1.0872	-11.58	***
D98							-1.9155	-15.12	***
Constant	3.0057	1.13		3.1068	1.64		1.4827	1.34	
R^2	0.6008			0.7113			0.7906		
N	41			201			250		
Root MSE	0.2318			0.1879			0.1600		

* significant at the 0.05 level
** significant at the 0.01 level
*** significant at the 0.001 level

Table 10: Laptop Adjacent Years

Variable	1990-1994 Coefficient	1990-1994 t-statistic	1994-1997 Coefficient	1994-1997 t-statistic	1997-1998 Coefficient	1997-1998 t-statistic
Disc	-0.1963	-3.74 ***	-0.0731	-1.77	-0.0133	-0.18
Lbat	0.0262	0.44	0.0961	3.03 **	0.0707	1.32
Lproc	0.1274	2.76 **	0.1119	3.04 **	0.3413	4.20 ***
Lhdsize	0.2104	5.28 ***	0.1922	6.01 ***	0.3054	4.49 ***
LRAM	0.1215	1.97 *	0.2403	6.36 ***	0.1067	1.43
Colour	0.2829	6.82 ***	0.3100	7.15 ***		
Lpix	0.0029	0.04	0.2065	2.16 *	0.0195	0.13
Ldiag	0.4183	1.93	0.8340	3.92 ***	1.9174	3.01 ***
Active	0.3077	5.13 ***	0.2241	3.62 ***	0.1222	2.15 *
Passive	0.0433	0.94	-0.0479	-0.84		
Lmspeed	0.0367	7.02 ***	0.0085	2.37 *	0.0032	0.83
Lcdspeed			0.0822	3.24 ***	-0.0471	-0.77
Major	0.2339	7.90 ***	0.1837	8.04 ***	0.2071	4.22 ***
Lithium			0.1315	2.65 **	0.0115	0.24
Nihyd	0.0606	2.29	0.0499	1.32		
Lweight	-0.1190	-1.20	-0.1344	-1.35	-0.2292	-1.27
Ldense	-0.0644	-0.70	0.0588	0.78	0.2384	2.14 *
Intel	0.0879	1.88	-0.0689	-1.17	0.0423	0.58
D91	-0.3039	-2.74 **				
D92	-0.9161	-7.51 ***				
D93	-1.4243	-9.48 ***				
D94	-1.7500	-10.34 ***				
D95			-0.4419	-7.72 ***		
D96			-0.9299	-11.54 ***		
D97			-1.4709	-14.01 ***		
D98					-0.8383	-12.52 ***
Constant	5.9957	6.32 ***	1.2351	1.08	-0.6047	-0.55
R^2	0.7273		0.7960		0.8216	
N	242		267		112	
Root MSE	0.1924		0.1477		0.1559	

* significant at the 0.05 level
** significant at the 0.01 level
*** significant at the 0.001 level

Table 11: Laptop Price Indexes

Model	1990	1991	1992	1993	1994	1995	1996	1997	1998	AAGR
Arithmetic Means	1.000	0.645	0.581	0.531	0.610	0.690	0.680	0.681	0.526	-7.7%
Pooled	1.000	0.693	0.356	0.211	0.147	0.098	0.062	0.037	0.018	-39.6%
Pooled with Interactions	1.000	0.696	0.359	0.211	0.146	0.099	0.058	0.034	0.017	-39.9%
Adjacent Years	1.000	0.653	0.382	0.214	0.160	0.113	0.067	0.039	0.017	-40.0%
Adjacent Years, Pooled	1.000	0.742	0.403	0.243	0.176	0.114	0.070	0.041	0.018	-39.6%
Regime 1: Monochrome	1.000	0.649								-35.1%
Regime 2: Transition			1.000	0.602	0.446					-33.2%
Regime 3: Colour						1.000	0.597	0.339	0.148	-47.0%
Chained using adjacent years	1.000	0.649	0.379	0.228	0.169	0.119	0.071	0.040	0.018	-39.6%
Pooled Technical	1.000	0.727	0.382	0.223	0.158	0.104	0.065	0.040	0.019	-39.2%
Pooled Technical, Interactions	1.000	0.732	0.387	0.224	0.156	0.104	0.059	0.037	0.018	-39.6%

Discussion

Overall, the approach of specifying the hedonic function using either direct measures of system performance or a set of technical proxies appears satisfactory. Despite a relatively parsimonious specification, model fit is good, with relatively low root MSE. Further, estimated coefficients display the expected sign, and most are statistically significant. Finally, estimated coefficients display reasonable stability across sub-periods.

Table 11 provides a summary of the price indexes calculated using all of the estimated hedonic functions. From the specifications without time interactions, the estimated AAGR in quality-adjusted prices is approximately -39%. Interestingly, the addition of the time interaction terms makes only a slight difference in the overall estimate of price change, resulting in an AAGR of approximately -40% per year.

Two approaches were used to account for the performance of laptop PCs: direct measures versus a set of technical proxies. The two approaches yielded nearly identical estimated price indexes, suggesting that the identified set of technical proxies (primarily the CPU*MHz interaction terms) can serve as an adequate measure of performance if direct measures of performance are unavailable. Further, the result that the "pure hardware" approach of technical proxies is nearly identical to the benchmark approach yields the somewhat unexpected finding that there are no significant interactions (either between hardware components or between hardware and operating system software) that are missed by the technical proxies approach.

As with prior research, a significant premium was supported for "major" brands. This dummy variable is likely serving as a proxy for overall quality, service, and warranty. These sources of user value are unfortunately unobservable in this data set. There is limited evidence from the technological regimes and adjacent years specifications that this premium has been declining over the sample time frame.

Chapter 5: Desktop Price Indexes

This chapter closely parallels Chapter 4 in developing price indexes for PCs using two approaches to specifying the hedonic function; however, the focus for this chapter is desktop, rather than laptop, systems. To avoid redundancy, this chapter will not reproduce the discussion presented in Chapter 4, but will instead focus on the results of applying the methods developed to this point.

Data

Data were again taken from *PC Magazine,* using the reviews of desktop PC systems presented each December from 1992-1998. The data set comprises 936 observations, following the removal of three models for which performance benchmarks were not run in the 1994 model year.[67] A summary of the variables is presented in Table 12, and selected means are presented in Table 13 and in Table 14. These machines were selected by the editors of *PC Magazine* to represent single-user systems, and were not considered to be either servers or mini-computers at the time of the reviews.

The trends in the desktop data closely parallel those for laptops, with the means of a number of variables increasing by one to two orders of magnitude (e.g., RAM, HD). As with laptops, distinction between "discount" and "list" prices was incorporated and tested with a dummy variable. However, unlike laptops, the estimated coefficient was not significant, and hence the distinction is dropped from the analysis.

As with laptops, a Major dummy variable was constructed. This variable includes brands that have 15 or more observations in the data set and are known to be priced above market rates. The Major dummy includes the brands AST, Compaq, DEC, Dell, IBM, and NEC. In addition, a Discount dummy variable was constructed to capture significant brands (15 or more observations) that were priced below market rates; this variable includes the brands Acer, Gateway, and Micro Express.

The *PC Magazine* reviews of desktops included consistent reports on warranties, which are reflected in three new variables: Lwcpu, Lwonsite, and Tech. The first two capture (the log of) the number of months for which the CPU is covered by warranty, and the number of months that on-site service is provided in the event of a breakdown, respectively. Tech is a dummy variable that captures whether the manufacturer provides on-line technical support to users.

Two further dummy variables are NIC and SCSI. The first captures whether the system includes a network interface card (NIC), while the second reports whether the system uses the faster, more expensive small computer systems interface (SCSI) with the hard disk instead of some variant of the more common IDE standard.

---

[67] In addition, nine models that used processors that were unique in this data set (e.g., the IBM "Blue Lightning") were removed because each was so different from typical processors that modeling them would have required a separate dummy variable for each one.

Table 12: Description of Desktop Variables

Variable	Description	Expected Effect
Lprice	Log of price	N/A
Lproc	Log of processor performance index	+
Lhdsize	Log of hard disk size (megabytes)	+
LRAM	Log of random access memory (megabytes)	+
Lscreen	Log of nominal diagonal screen size (inches)	+
Lvram	Log of video card RAM (kilobytes)	+
Lmspeed	Log of internal modem maximum speed (bps)	+
Lcdspeed	Log of maximum CD-ROM speed	+
Lwcpu	Log of length of warranty on the CPU (months)	+
Lwonsite	Log of length of on-site warranty (months)	+
Tech	Dummy variable for telephone technical support	+
NIC	Dummy variable for network interface card	+
SCSI	Dummy variable for SCSI hard drive interface	+
Intel	Dummy variable for Intel CPU	+
Major	Dummy variable for major brands	+
Discount	Dummy variable for discount brands	+
D286	Dummy variable for 286 CPU	+
D386	Dummy variable for 386 CPU	+
D486	Dummy variable for 486 CPU	+
D586	Dummy variable for Pentium CPU	+
D686	Dummy variable for Pentium-Pro CPU	+
D786	Dummy variable for Pentium-II CPU	+
DK6	Dummy variable for K6 CPU	+
DK6-2	Dummy variable for K6-2 CPU	+
LMHz	Log of processor clock speed in MHz	+
LMHz286	LMHz * D286 interaction term	+
LMHz386	LMHz * D386 interaction term	+
LMHz486	LMHz * D486 interaction term	+
LMHz586	LMHz * D586 interaction term	+
LMHz686	LMHz * D686 interaction term	+
LMHz786	LMHz * D786 interaction term	+
LMHzK6	LMHz * DK6 interaction term	+
LMHzK62	LMHz * DK6-2 interaction term	+
LL1Cache	Log of level 1 (on chip) cache memory (kilobytes)	+
LL2Cache	Log of level 2 cache memory (kilobytes)	+

Table 13: Means of Selected Desktop Variables

Year	n	Price	RAM	HD	Mspeed	CD	Scrn	Vram
1992	205	$3,023.37	8.2	226	0	0.00	14.1	1012
1993	178	$3,221.98	16.0	397	121	0.08	14.2	1179
1994	161	$3,080.24	13.3	628	1819	2.16	15.2	1946
1995	103	$3,319.87	16.0	1201	8668	4.30	15.7	2287
1996	91	$3,185.03	23.0	2262	12554	7.66	16.6	3343
1997	97	$2,623.63	64.0	4667	26221	20.93	15.6	5088
1998	101	$2,238.16	109.6	9924	22416	32.32	17.4	8233

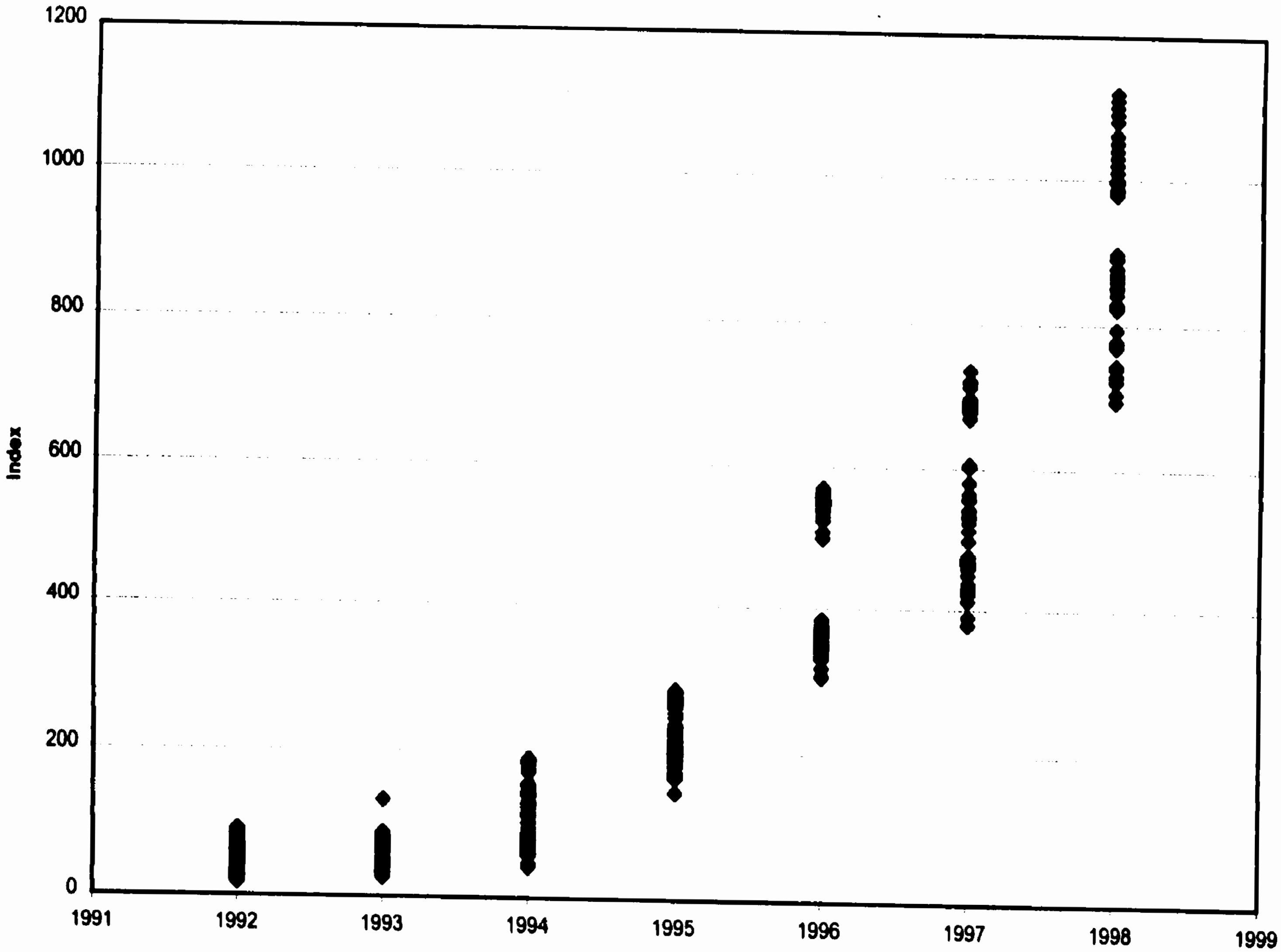
Table 14: Means of Desktop Performance Variables

Year	MHz	Proc	L1	L2	386	486	586	686	786	K6	K6-2
1992	37.8	46.4	7.2	186.4	21	184	0	0	0	0	0
1993	47.8	56.8	8.0	94.6	0	177	1	0	0	0	0
1994	75.0	126.0	13.3	264.7	0	67	94	0	0	0	0
1995	116.0	226.8	16.0	293.3	0	0	103	0	0	0	0
1996	200.0	442.2	16.0	348.8	0	0	51	40	0	0	0
1997	249.7	611.6	35.3	506.7	0	0	24	0	63	10	0
1998	395.7	990.7	34.5	522.1	0	0	0	0	93	0	8

As with the data set for laptops, there is an almost complete absence of matched models in this data set. Thus, Age and Vintage variables are again not included.

Again, both the technical proxies and benchmark approaches will be used to specify the hedonic function. Application of the scaling procedure described in Chapter 3 produced processor index values for all models in the data set, which are depicted in Figure 5. The fitting of an exponential trend the data indicates that, in this sample, performance was doubling approximately every 15.1 months. This rate of doubling is nearly identical to that derived for laptops (14.5 months).

Figure 5: Desktop Processor Index



Benchmark Specification

As with laptops, the double-log functional form was used, although a Box-Cox test neither confirms nor wildly rejects this specification (λ = -0.1467, and the 95% confidence interval ranges from -0.2731 to -0.0085).[68]

The results of the pooled benchmark specification are presented in Table 15. As with laptops, all standard errors and hypothesis tests are computed using the White heteroskedasticity-robust procedure. Most coefficients display the predicted sign with statistical significance. All of Lproc, Lhdsize, LRAM, Lscreen, Lmspeed, SCSI, Lwcpu, Lwonsite, Major, Discount, and Intel are significant at the $p < 0.05$ level or higher. Unexpectedly, none of Lvram, Lcdspeed, NIC, or Tech are significant. Major sources of user value appear to be related to performance (Lproc, Lhdsize, LRAM, Lmspeed, SCSI), warranty (Lwcpu, Lwonsite), and the display (Lscreen). Finally, applying the dummy variable technique yields the AAGR in quality adjusted prices to be -31.6% over the period 1992-1998.

As with laptops, an interaction specification was tested. Interaction terms were constructed between a time counter variable and the numerical variables displaying a trend in the linear specification. The time counter variable is set to zero in 1992, and increases by one in each subsequent year. Interaction variables were created with each of: Lproc, Lhdsize, LRAM, Lscreen, Lvram, Lmspeed, and Lcdspeed. However, an F-test failed to reject the null hypothesis that all of Lhdsize, LRAM, Lscreen, Lvram, and Lmspeed were equal to zero. The only significant interaction terms were Time*Lproc and Time*Lcdspeed. The results of the model with these two interaction terms are also presented in Table 15.

[68] The double log was used in place of the Box-Cox transformation for the sake of comparability with the Laptop results and with prior research. Given the relatively small deviation of Lambda from zero, the transformation is unlikely to have substantially affected the results.

Table 15: Desktop Pooled Benchmark Specifications

	Linear Model		Interactions Model	
Variable	Coefficient	t-statistic	Coefficient	t-statistic
Lproc	0.2712	9.37 ***	0.2052	5.76 ***
Lhdsize	0.0547	2.71 **	0.0519	2.70 **
LRAM	0.1986	6.08 ***	0.1174	3.30 ***
Lscreen	1.1488	9.42 ***	1.0746	9.00 ***
Lvram	0.0155	0.67	0.0009	0.04
Lmspeed	0.0040	2.29 *	-0.0083	-1.68
Lcdspeed	0.0491	1.35	0.0605	1.60
SCSI	0.2056	9.76 ***	0.2015	9.72 ***
NIC	-0.0269	-1.12	0.0268	0.93
Lwcpu	0.0220	1.97 *	0.0247	2.21 *
Lwonsite	0.0167	3.15 **	0.0166	3.19 ***
Tech	0.0059	0.30	0.0021	0.11
Major	0.1769	9.16 ***	0.1725	9.04 ***
Discount	-0.1396	-6.61 ***	-0.1339	-6.18 ***
Intel	0.0843	2.27 *	0.0602	1.66
D93	-0.1567	-5.43 ***	-0.3568	-5.25 ***
D94	-0.5697	-11.34 ***	-1.1157	-7.13 ***
D95	-0.7882	-10.69 ***	-1.7379	-6.55 ***
D96	-1.2644	-13.05 ***	-2.7085	-6.77 ***
D97	-1.6876	-13.00 ***	-3.6002	-6.81 ***
D98	-2.2871	-14.96 ***	-4.7791	-7.01 ***
Constant	2.8744	8.81 ***	3.6227	9.67 ***
Time*Lproc			0.0690	3.56 ***
Time*Lcdspeed			0.0032	2.57 **
R^2	0.6112		0.6181	
N	936		936	
Root MSE	0.1813		0.1792	

* significant at the 0.05 level
** significant at the 0.01 level
*** significant at the 0.001 level

The coefficients on both of the interaction terms are positive, indicating that the price of performance and CD-ROM speed both increase over time in the sample, relative to the average rate of change embodied in the year dummies. The time interactions model presents only a modest increase in explanatory power (root MSE is reduced by 1.2%), and makes only a modest difference to the overall resulting AAGR of -30.4%. This result indicates that the linear model may have been overstating price change by constraining the implicit price of performance and CD-ROM speed to be changing at the same rate as all other attributes.

The finding that there are no significant interaction terms with any of RAM, hard disk size, monitor size, modem speed, or video RAM implies that the implicit prices of these attributes have been changing over time approximately the same rate, and that this rate is adequately captured by the year dummy variables in the pooled specifications.

Equivalence of Benchmark and Proxies

To test the assertion that microcomputer performance could be adequately modelled by the technical proxies suggested above, these proxies were regressed on the performance index. The results of this exercise are presented in Table 16. Dummy variables for generations of processors were not included in order to constrain the effects of MHz (within generations) to be comparable across generations.

Table 16: Proxies Regressed on Desktop Processor Index

Variable	Coefficient	t-statistic
LL1cache	0.1093	3.18 **
LL2cache	0.0256	3.40 ***
LMHz386	0.6656	27.34 ***
LMHz486	0.7466	72.07 ***
LMHz586	0.8764	88.22 ***
LMHz686	0.9543	100.44 ***
LMHz786	0.9280	87.76 ***
LMHzK6	0.9020	60.47 ***
LMHzK62	0.9044	63.20 ***
LRAM	0.0076	0.59
Constant	0.7768	11.23 ***
R^2	0.9925	
N	936	
Root MSE	0.1000	

** significant at the 0.01 level
*** significant at the 0.001 level

As with the laptop data, the model fit is good, displaying a high R^2 (0.99) and low root mean-squared error. Once again, all of the CPU-by-MHz coefficients have the expected sign and display strong statistical significance. By and large, the coefficients display the expected ranking; however, the estimated coefficient for the Pentium-Pro processor (686) is larger than that for the Pentium-II processor (786). This result validates the continued use of the Pentium-Pro for commercial servers despite the availability of the Pentium-II and Pentium-III processors. Likewise, the coefficients on the L1 and L2 cache memories display the expected ranking, with a kilobyte of L1 cache having approximately 4 times the effect of a kilobyte of L2 Cache. Finally, RAM is not a statistically significant contributor to the desktop processor index, again confirming that the Ziff-Davis processor benchmarks are independent of RAM.

Technical Proxies Specification

The results of an alternative specification using technical proxies, rather than the performance index, are presented in Table 17. Interaction terms were constructed using the same approach as with the benchmark method, although the only interaction to emerge as significant is Time by LRAM. Several points are worth noting. First, note that the two indexes produced by the technical specifications closely approximate each other: the AAGR's for the proxy specification are -35.2% and -35.3% (without and with interaction terms, respectively). However, these two estimates differ from the estimates using the benchmark approach (-31.6% and -30.4%, without and with interaction terms). Given the slight improvement in adjusted R^2 and root MSE in the technical approach, the technical approach is the preferred specification. Second, the estimated coefficients for the variables common to both specifications retain the same sign, approximate magnitude, and approximate degree of statistical significance. Third, the majority of estimated coefficients for the CPU by MHz proxies display the same relative ranking as those in the regression of the proxies on the index, presented in Table 16. Fourth, it is hypothesised that the Time*LRAM interaction, by virtue of the high correlation between Proc and RAM, is serving as a proxy for the Time*Proc interaction, which is obviously not included in the technical proxies specification.

Table 17: Desktop Pooled Technical Specifications

Variable	Linear Model Coefficient	Linear Model t-statistic	Interactions Model Coefficient	Interactions Model t-statistic
LL1cache	-0.0533	-0.58	0.1661	1.67
LL2cache	0.0231	1.16	0.0217	1.09
LMHz386	0.1760	2.75 **	0.3094	4.52 ***
LMHz486	0.2411	8.69 ***	0.2365	8.56 ***
LMHz586	0.2817	9.09 ***	0.2769	8.98 ***
LMHz686	0.2668	7.97 ***	0.2694	8.22 ***
LMHz786	0.3186	9.92 ***	0.3154	9.86 ***
LMHzK6	0.3006	7.53 ***	0.2684	6.58 ***
LMHzK6-2	0.2835	7.02 ***	0.2535	6.21 ***
Lhdsize	0.0545	2.89 **	0.0525	2.85 **
LRAM	0.2946	5.49 ***	-0.0653	-0.79
LScreen	1.1429	9.60 ***	1.1070	9.38 ***
Lvram	0.0204	0.91	0.0188	0.85
Lmspeed	0.0029	1.76	0.0025	1.50
Lcdspeed	0.0267	0.72	0.0312	0.84
SCSI	0.2045	9.74 ***	0.2038	9.82 ***
NIC	-0.0068	-0.27	0.0010	0.04
Lwcpu	0.0248	2.22 **	0.0237	2.13 *
Lwonsite	0.0167	3.20 ***	0.0176	3.38 ***
Tech	0.0002	0.01	0.0008	0.05
Major	0.1782	9.34 ***	0.1753	9.24 ***
Discount	-0.1293	-6.59 ***	-0.1314	-6.62 ***
Intel	0.0334	0.82	0.0265	0.66
D93	-0.2137	-4.64 ***	-0.1815	-4.61 ***
D94	-0.5973	-11.48 ***	-0.9136	-10.67 ***
D95	-0.8380	-11.00 ***	-1.3646	-10.11 ***
D96	-1.2847	-12.86 ***	-2.0223	-10.91 ***
D97	-1.9212	-13.72 ***	-3.0633	-10.87 ***
D98	-2.6198	-15.63 ***	-4.1320	-11.48 ***
Constant	2.8718	7.69 ***	3.2911	8.51 ***
Time*LRAM			0.0771	4.84 ***
R^2	0.6319		0.6363	
N	936		936	
Root MSE	0.1764		0.1754	

* significant at the 0.05 level
** significant at the 0.01 level
*** significant at the 0.001 level

Resulting Price Indexes

Price indexes were constructed using all four specifications of the hedonic function and applying the dummy variable approach.[69] The resulting indexes and average annual growth rates (AAGR) are presented in Table 18. For the models involving the time interaction terms, the log change in price is computed using the average component values across periods t and $t+1$, as in Berndt and Griliches (1990) and Baker (1997).

Table 18: Desktop Price Indexes

Model	1992	1993	1994	1995	1996	1997	1998	AAGR
Arithmetic Means	1.000	1.066	1.019	1.098	1.053	0.868	0.740	-4.9%
Pooled	1.000	0.855	0.566	0.456	0.284	0.187	0.103	-31.6%
with Interactions	1.000	0.928	0.608	0.488	0.297	0.205	0.113	-30.4%
Pooled Technical	1.000	0.808	0.551	0.434	0.278	0.148	0.074	-35.2%
with Interactions	1.000	1.007	0.597	0.470	0.309	0.148	0.073	-35.3%

Discussion

The results for desktop PCs, when examined with the results from laptop PCs, highlight two findings. First, the identified set of technical proxies are able to reproduce the performance index in an economically meaningful manner. Second, the pooled models with interaction terms appear to provide nearly identical estimates of the rate of quality adjusted price decline whether the underlying hedonic function is based on the benchmarks or technical proxies approach. As mentioned in Chapter 4, this finding highlights the apparent absence of interactions (either between hardware components or between hardware and operating system software) that affect performance.

Interestingly, the incorporation of the warranty dummy variables somewhat reduced the estimated price premium for Major brands (0.206 without warranty variables versus 0.177 with). This results suggests that, as hypothesised elsewhere, brand dummies are indeed serving as proxies for unobserved dimensions of quality. In this case, the data permitted explicit modelling of the warranty aspect of this quality.

Using the results from the interactions approaches, it appears that in the 1990s, laptop PCs have declined in quality-adjusted terms at about 39% per year, while desktop PCs have declined at approximately 35% per year.

[69] For all calculations of indexes using the dummy variable approach, the standard correction factor of one-half the squared standard error of the estimated coefficient has been added.

Chapter 6: Contributions, Limitations, and Future Research

Contributions

The problem of measuring quality and price change in computer systems has been an active area of research for more than thirty years. This dissertation makes three principal contributions to this body of work.

First, the Delphi Survey presented in Chapter 3 provides the first known empirical assessment of the sources of user value in microcomputer systems. These results, along with the judgement of the author, have guided the various specifications of the hedonic function estimated in this paper. The resulting functions are considerably more parsimonious than prior specifications, yet have also achieved a better fit with the data, as measured on a number of dimensions: higher R^2, lower root MSE, and estimated coefficients that are correctly signed and statistically significant. These specifications can guide future research on the topic.

Second, this paper constructed a processor performance index based on published benchmark tests. This index was tested in the hedonic functions for both laptop and desktop PCs, and displayed good explanatory power. This is the first known use of benchmark results in the construction of price indexes for microcomputers using hedonic methods.

Third, this paper constructed a novel set of technical proxies for performance. These proxies were not only shown to almost perfectly reproduce the performance index described above, but were also demonstrated to be a nearly equivalent way of operationalising performance in the hedonic function. Thus, these proxies could be used with larger, more general data sets for which performance measures have not been taken.

This paper also makes a number of more minor contributions, which include: (i) the introduction of the notion of distinct technological eras or "regimes," during which technological change occurs along a number of dimensions and across which different dimensions of change are introduced; (ii) the construction of more recent price indexes for desktop and laptop PCs which can be used as an input to further econometric work; (iii) the exploration of brands and pricing behaviour; and (iv) the beginning of the exploration of complementarities within microcomputer systems through the use of performance benchmarks that capture interactions between hardware subsystems and between hardware and operating system software.

Limitations

The primary limitation of this research is the relatively sparse set of data for which performance measurements are available. Limiting the sample to machines for which published performance measures are available introduces the potential that the sample may not be representative of the universe of machines in any given year. While unlikely to be a source of bias in the price index, the small samples will certainly increase the "noise" or measurement error.

A more serious limitation of this data set is the unavailability of corresponding data on shipments or sales of models. Lacking this information, the dummy variable method has been used to compute price indexes. More sophisticated techniques, such as the Divisia index, could not be applied. Even though previous estimates that have used quantity weights have differed little from unweighted estimates, the incorporation of the techniques developed in this dissertation with more sophisticated index construction techniques remains a key direction for future research.

The lack of quantity data has also prevented the estimation of reservation prices for "new goods" (e.g., CD-ROMs) in the period prior to their introduction. Thus, the indexes calculated here reflect the new goods problem, and as such, are likely underestimates of the true rate of price change. However, the magnitude of any such new goods biases is likely very small in comparison to the overall index numbers, given: (i) the relatively small number and cost of "new goods" in the data set, and (ii) the very large overall rate of price change in computer systems.

Finally, the issue of the appropriate functional form of the hedonic function has not been explored. In this paper, the double-log specification was used. However, forms consistent with t-identification and "bowed-out" hedonic contours were not tested, and this issue is also left for future work. While this topic is certainly of methodological interest, choices around functional form and index number construction have been shown to have far less impact on the computed indexes than the specification of the hedonic function.

Future Research

By providing novel approaches to addressing the measurement of price and quality change in microcomputers, this dissertation has contributed to the development of a number of streams of research. Two major categories of future work include the continued refinement of microcomputer price indexes as well as the application of these indexes to address other questions.

Further Development of Price Indexes

As mentioned in the limitations above, future work would ideally involve a larger data set that more accurately reflects the universe microcomputers and a longer time frame. Likely using variants of the technical proxies identified here, this work can incorporate quantity information to address: (i) the estimation of reservation prices for new goods prior to their introduction (colour screens, active matrix displays, CD-ROMs, etc.) to avoid the new goods bias; (ii) chaining technological regimes together; and (iii) constructing price indexes using the more sophisticated approaches, such as the characteristics prices, composite or imputed prices, and Divisia. As mentioned above, the issue of functional form should be explored, likely with a flexible form such as the normalised quadratic that both permits "bowed-out" hedonic contours that can cross the axes, permitting the estimation of reservation prices.

Further work on performance measurement could be undertaken toward at least two ends: a performance index for graphics subsystems and an application index assessing overall system performance. It remains to be seen whether these indexes will capture aspects of performance that command a price premium, or whether they go unpriced, as is apparently the case with the hard disk throughput index.

Figure 6: Chwelos and BGR Indexes

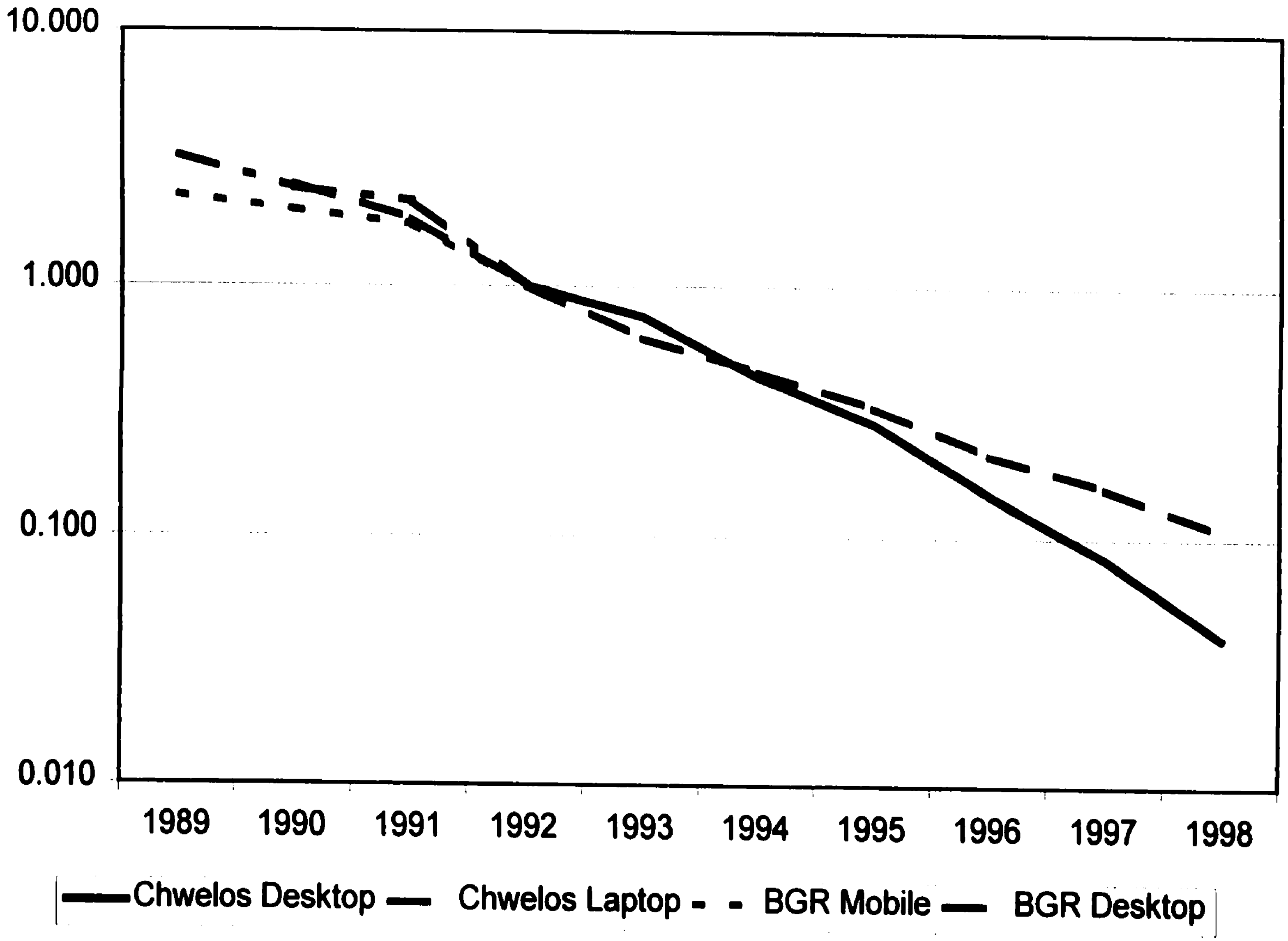


Figure 7: Laptop Indexes

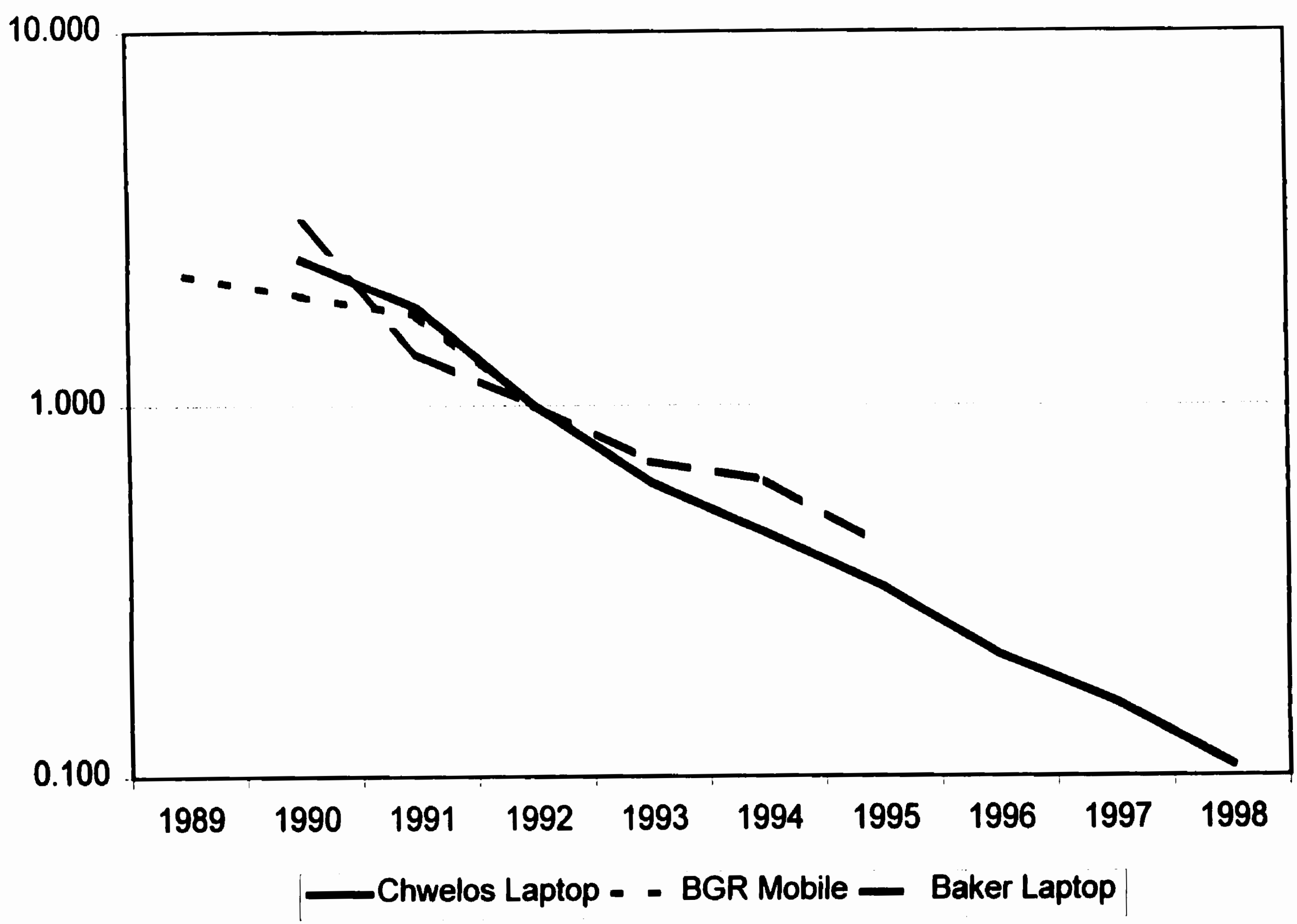
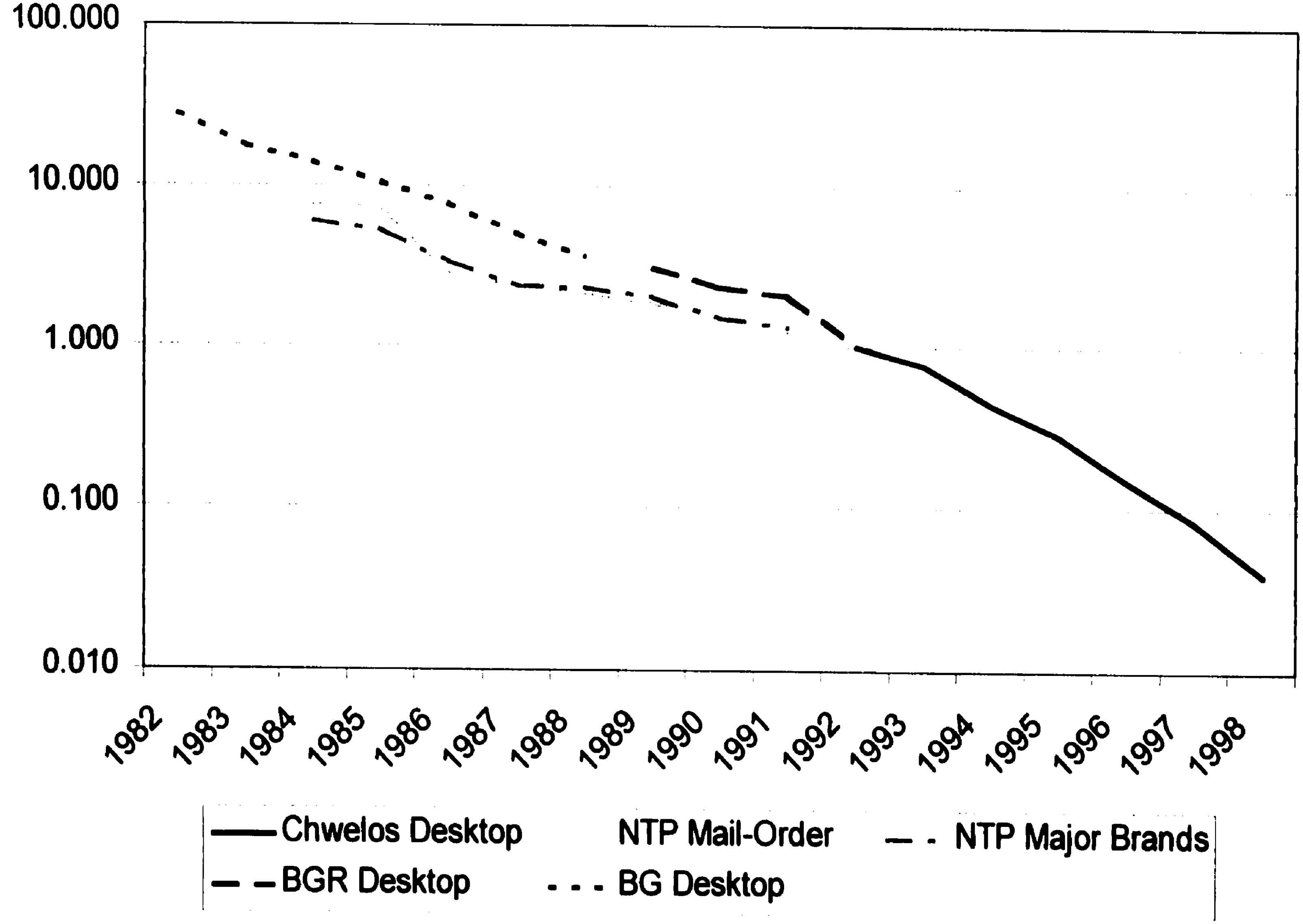


Figure 8: Desktop Indexes



Applications of the Price Indexes

The price indexes developed here, as well as those resulting from the extensions proposed above, can be used to address a number of questions. Primarily, accurate measures of input cost change over time can be used as an input to empirical research on the "productivity paradox" of information technology (addressed in Appendix 1). For example, work assessing the firm-level returns to spending on information technology require accurate measures of real capital stock (as well as of other inputs and output); construction of a estimate of real IT capital stock is probably best done using annual data on spending in conjunction with input-cost indexes.

The price indexes developed in this paper provide a more accurate measure of the true rate of price change in PC systems through their improved measure of "quality," as defined from a user-value perspective. (See Figure 6 for a comparison to the BGR indexes, Figure 7 for the laptop indexes, and Figure 8 for the desktop indexes.) Given that these indexes are larger in absolute magnitude than those derived from previous work on microcomputers, it would be interesting to explore the implications of these price indexes for the overall Consumer Price Index (CPI). Factoring in a significantly larger rate of price decline for microcomputer hardware would further highlight the degree to which the CPI has been overstating inflation in most western countries for at least the last ten years.

The resulting indexes should also be of interest to practitioners. While there is nothing in the way of a theoretical law underpinning the rate of price declines produced in this paper, the rate of change over time as a result of the interaction of numerous technical innovations as well as market forces appears to be reasonably stable. Thus, it may be fruitful to extrapolate these trends into the near future, expecting approximately a 39% annual price decline for laptops versus 35% for desktop machines. These figures may assist in planning a firm's purchase pattern for IT hardware, as well as assisting in making lease versus buy decisions.

References

Forbes, (1980), 24.

"The value of BC Tel Systems," *Conversation With BC Tel IS Executive*, (1995).

Technology, Productivity, and Job Creation. Paris, France: Organization for Economic Cooperation and Development, 1996.

"Paradox Lost," *The Economist*, 340, 7985 (1996), s13-s16.

Adler M. and E. Ziglio, Editors. *Gazing into the Oracle: The Delphi Method and its Application to Social Policy and Public Health*. Bristol, PA: Jessica Kingsley, 1996.

Applegate L. M., F. W. McFarlan, and J. L. McKenney, *Corporate Information Systems Management: Text and Cases*. 5th edition. Boston, MA: Irwin McGraw-Hill, 1999.

Arguea N. and C. Hsiao, "Econometric Issues of Estimating Hedonic Price Functions with Application to the U.S. Market for Automobiles," *Journal of Econometrics*, 56, (1993), 243-67.

Baily M. N. and R. J. Gordon, "The Productivity Slowdown, Measurement Issues, and Explosion of Computer Power," *Brookings Papers on Economic Activity*, 2, (1988).

Baker T. A., "Quality-Adjusted Price Indexes for Portable Computers," *Applied Economics*, 29, 9 (1997), 1115-23.

Barua A., C. H. Kriebel, and T. Mukhopadhyay, "Information Technology and Business Value: An Analytic and Empirical Investigation," *Information System Research*, 6, 1 (1995), 3-23.

Barua A. and B. Lee, "The Information Technology Productivity Paradox Revisited: A Theoretical and Empirical Investigation in the Manufacturing Sector," *The International Journal of Flexible Manufacturing Systems*, 9, 2 (1997), 145-66.

Berndt E. R., *The Practice of Econometrics: Classic and Contemporary*. Reading, MA: Addison-Wesley, 1991.

Berndt E. R. and Z. Griliches, "Price Indexes for Microcomputers: An Exploratory Study," *National Bureau of Economic Research Working Paper Series, 3378*, (1990).

Berndt E. R., Z. Griliches, and N. J. Rappaport, "Econometric Estimates of Price Indexes for Personal Computers in the 1990's," *Journal of Econometrics,* 68, 1 (1995), 243-68.

Berndt E. R. and C. J. Morrison, "High-tech Capital Formation and Economic Performance in U.S. Manufacturing Industries: An Exploratory Analysis," *Journal of Econometrics,* 65, (1995), 9-43.

Bradley S. P. and S. Foley, "Wal-Mart Stores, Inc.," *Harvard Business School Case 9-794-024,* (1994).

Bresnahan T. F., "Measuring the Spillovers from Technical Advance: Mainframe Computers in Financial Services," *American Economic Review,* 76, (1986), 742-55.

Brydon M. J., P. D. Chwelos, D. Jung, and E. L. Smythe, "A Comprehensive Method for Business Process Reengineering," *University of British Columbia Working Paper,* (1995).

Brynjolfsson E., "The Productivity Paradox of Information Technology," *Communications of the ACM,* 36, 12 (1993), 67-77.

-----, "The Contribution of Information Technology to Consumer Welfare," *Information Systems Research,* 7, 3 (1996), 281-300.

Brynjolfsson E. and L. Hitt, "Is Information Systems Spending Productive? New Evidence and New Results," *Proceedings of the International Conference on Information Systems,* 1993.

-----, "Information Technology as a Factor of Production: The Role of Differences among Firms," *Economics of Innovation and New Technology,* 3, 4 (1995), 183-99.

-----, "Paradox Lost? Firm-level Evidence on the Returns to Information Systems Spending," *Management Science,* 42, 4 (1996), 541-58.

Brynjolfsson E. and C. F. Kemerer, " Network Externalities in Microcomputer Software: An Econometric Analysis of the Spreadsheet Market," *Management Science,* 42, 12 (1996), 1627-47.

Brynjolfsson E., T. W. Malone, V. Gurbaxani, and A. Kambil, "Does Information Technolgy Lead to Smaller Firms?," *Management Science,* 40, 12 (1994), 1628-44.

Cartwright D. W., "Improved Deflation of Purchases of Computers," *Survey of Current Business,* 66, 3 (1986), 7-9.

Cartwright D. W. and S. D. Smith, "Deflators for Purchases of Computers in GNP: Revised and Extended Estimates, 1983-88," *Survey of Current Business,* 68, 11 (1988), 23-4.

Caudill S. B. and D. M. Gropper, "A Quality-Adjusted Price Index for Mainframe Computers," *Applied Economics,* 29, 12 (1997), 1605-10.

Chow G. C., "Technological Change and the Demand for Computers," *American Economic Review,* 57, 5 (1967), 1117-30.

Clemons E. K., "Evaluation of Strategic Investments in Information Technology," *Communications of the ACM,* 34, 1 (1991), 22-36.

Cole R., Y. C. Chen, J. A. Barquin-Stolleman, E. Dulberger, N. Helvacian, and J. H. Hodge, "Quality-Adjusted Price Indexes for Computer Processors and Selected Peripheral Equipment," *Survey of Current Business,* 66, (1986), 41-50.

Cole R., E. Dulberger, and J. E. Triplett, Comments on Chapter 3 (Gordon). Jorgenson D. W. and R. Landau, Editors. *Technology and Capital Formation.* Cambridge, MA: MIT Press, 1989: 215-9.

Court A. T., in: Roos C. F., Editor. *The Dynamics of Automobile Demand.* New York, NY: The General Motors Corporation, 1939: 99-117.

Cron W. L. and M. G. Sobol, "The Relationship Between Computerization and Performance: A Strategy for Maximizing the Economic Benefits of Computerization," *Information & Management,* 6, 3 (1983), 171-81.

Dalkey N. and O. Helmer, "An Experimental Application of the DELPHI Method to the Use of Experts," *Management Science,* 9, (1963), 458-67.

Davenport T. H., *Process Innovation: Reengineering Work Through Information Technology.* Boston, MA: Harvard Business School Press, 1993.

David P. A., "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox," *American Economic Review,* 80, 2 (1990), 355-61.

Dean E. R., "The Accuracy of the BLS Productivity Measures," *Monthly Labor Review,* 122, 2 (1999), 24-34.

Delbecq A. L., A. H. Van de Ven, and D. H. Gustafson, *Group Techniques for Program Planning: A Guide to the Nominal Group and Delphi Processes.* Glenview, IL: Scott-Foresman, 1975.

Diewert W. E., "Exact and Superlative Index Numbers," *Journal of Econometrics*, 4, 2 (1976), 115-45.

----, Index Numbers. Eatwell J., M. Milgate, and P. Newman, Editors. *The New Palgrave: A Dictionary of Economics.* Vol. 2. London: MacMillian Press, 1987: 767-80.

----, Hedonic Methods in Statistical Agency Environments: An Intellectual Biopsy: Comment. Berndt E. R. and J. E. Triplett, Editors. *Fifty Years of Economic Measurement: The Jubilee of the Conference on Research in Income and Wealth.* Vol. 54. Chicago, IL: University of Chicago Press, 1990: 233-7.

----, "Comment on CPI Biases," *Business Economics*, 31, 2 (1996), 30-5.

Diewert W. E. and K. Fox, "Can Measurement Error Explain the Productivity Paradox?," *Proceedings of the CSLS Conference on Service Sector Productivity and the Productivity Paradox*, 1997.

DiNardo J. E. and J.-S. Pische, "The Returns to Computer Use Revisited: Have Pencils Changed the Wage Structure Too?," *National Bureau of Economic Research Working Paper Series*, 5606, (1996).

Dos Santos B. L., K. Peffers, and D. C. Mauer, "The Impact of Information Technology Investment Announcements on the Market Value of the Firm," *Information Systems Research*, 4, 1 (1993), 1-23.

Dulberger E., The Application of a Hedonic Model to a Quality-Adjusted Price Index for Computer Processors. Jorgenson D. W. and R. Landau, Editors. *Technology and Capital Formation.* Cambridge, MA: MIT Press, 1989: 37-75.

Eldridge L. P., "How Price Indexes Affect BLS Productivity Measures," *Monthly Labor Review*, 122, 2 (1999), 35-46.

Fisher F. M., J. J. McGowan, and J. E. Greenwood, *Folded, Spindled, and Mutilated: Economic Analysis and U.S. v. IBM.* Cambridge, MA: The MIT Press, 1983.

Flamm K., *Targeting the Computer.* Washington, D.C.: The Brookings Institution, 1987.

Francalanci C. and H. Galal, "Information Technology and Worker Composition: Determinants of Productivity in the Life Insurance Industry.," *Management Information Systems Quarterly*, 22, 2 (1998), 227-41.

Gandal N., "Hedonic Price Indexes for Spreadsheets and an Empirical Test for Network Externalities," *RAND Journal of Economics*, 25, 1 (1994), 160-70.

Gordon R. J., The Postwar Evolution of Computer Prices. Jorgenson D. W. and R. Landau, Editors. *Technology and Capital Formation.* Cambridge, MA: MIT Press, 1989a: 77-125.

-----, Comments on Chapter 4 (Tripett) and Rejoinder to the Cole-Dulberger-Triplett Comments. Jorgenson D. W. and R. Landau, Editors. *Technology and Capital Formation.* Cambridge, MA: MIT Press, 1989b: 221-4.

-----, *The Measurement of Durable Goods Prices.* Chicago, IL: University of Chicago Press, 1990.

-----, "Problems in the Measurement and Performance of Service-Sector Productivity in the United States," *National Bureau of Economic Research Working Paper Series, 5519,* (1996).

Greenspan A., "The American Economy in a World Context," *35th Annual Conference on Bank Structure and Competition of the Federal Reserve Bank of Chicago.*

Griliches Z., Hedonic Price Indexes for Automobiles: An Econometric Analysis of Quality Change. in. *The Price Statistics of the Federal Government, General Series No. 73.* New York, NY: Columbia University Press, 1961: 137-96.

-----, Introduction: Hedonic Price Indexes Revisited. Griliches Z., ed. *Price Indexes and Quality Change: Studies in New Methods of Measurement.* Cambridge, MA: Harvard University Press, 1971: 3-15.

-----, "Issues in Assessing the Contribution of R&D to Productivity Growth," *Bell Journal of Economics,* 10, 2 (1979), 92-116.

-----, Hedonic Price Indexes and the Measurement of Capital and Productivity: Some Historical Reflections. Berndt E. R. and J. E. Triplett, Editors. *Fifty Years of Economic Measurement: The Jubilee of the Conference on Research in Income and Wealth.* Vol. 54. Chicago, IL: University of Chicago Press, 1990: 185-205.

-----, "Productivity, R&D, and the Data Constraint," *American Economic Review,* 84, 1 (1994), 1-23.

Hamermesh D. S. and S. M. Oster, "Tools or Toys? The Impact of High Technology on Scholarly Productivity," *NBER Working Paper,* 6761, (1998), 1-37.

Hammer M. and J. Champy, *Reengineering the Corporation: A Manifesto for Business Revolution.* New York, NY: Harper Business, 1993.

Harhoff D. and D. Moch, "Price Indexes for PC Database Software and the Value of Code Compatibility," *Research Policy,* 25, 4-5 (1997), 509-20.

Hitt L. and E. Brynjolfsson, "The Three Faces of IT Value: Theory and Evidence," *Proceedings of the International Conference on Information Systems*, 1994.

Hoffmann J., "Problems of Inflation Measurement in Germany," *Discussion Paper, Economic Research Group of the Deutsche Bundesbank*, (1998).

Kendall J. W., "Variations of Delphi," *Technological Forecasting and Social Change*, 11, (1977), 78-85.

Knight K. E., "Changes in Computer Performance: A Historical View," *Datamation*, 12, 9 (1966), 40-54.

Krueger A., "How Computers Have Changed the Wage Structure: Evidence from Microdata, 1984-1989," *Quarterly Journal of Economics*, 108, (1993), 410-42.

Kwon M. J. and P. Stoneman, "The Impact of Technology Adoption on Firm Productivity," *Economics of Innovation and New Technology*, 3, 4 (1995), 219-33.

Landauer T. K., *The Trouble with Computers: Usefulness, Usability, and Productivity.* Cambridge, Massachusetts: MIT Press, 1995.

Lehr W. and F. R. Lichtenberg, "Computer Use and Productivity Growth in Federal Government Agencies, 1987 to 1992," *NBER Working Paper 5616*, (1996), 1-32.

-----, "Information Technology and Its Impact on Firm-level Productivity: Evidence from Government and Private Data Sources, 1977-1993," *Proceedings of the CSLS Conference on Service Sector Productivity and the Productivity Paradox*, Ottawa, 1997.

Lichtenberg F. R., "The Output Contributions of Computer Equipment and Personnel: A Firm-Level Analysis," *Economics of Innovation and New Technology*, 3, 4 (1995), 201-17.

Lipsey R. E., Hedonic Price Indexes and the Measurement of Capital and Productivity: Comment. Berndt E. R. and J. E. Triplett, Editors. *Fifty Years of Economic Measurement: The Jubilee of the Conference on Research in Income and Wealth.* Vol. 54. Chicago, IL: University of Chicago Press, 1990: 202-5.

Lohr S., "Computer Age Gains Respect of Economists," *New York Times*, (1999).

Loveman G. W., An Assessment of the Productivity Impact of Information Technologies. Allen T. J. and M. S. Scott Morton, Editors. *Information Technology and the Corporation of the 1990s: Research Studies.* Cambridge, MA: MIT Press, 1994: 84-110.

Mandel M. J., "The Real Truth about the Economy," *Business Week*, 124, 45 (1994), 110-8.

Morrison C. J. and E. R. Berndt, "Assessing the Productivity of Information Technology Equipment in U.S. Manufacturing Industries," *National Bureau of Economic Research Working Paper Series*, 3582, (1991).

Mukhopadhyay T. and R. B. Cooper, "A Microeconomic Production Assessment of the Business Value of Management Information Systems: The Case of Inventory Control," *Journal of Management Information Systems*, 10, 1 (1993), 33-55.

Mukhopadhyay T., S. Kekre, and S. Kalathur, "Business Value of Information Technology: A Study of Electronic Data Interchange," *Management Informations Systems Quarterly*, 19, 2 (1995), 137-56.

Mukhopadhyay T., F. J. Lerch, and V. Mangal, "Assessing the Impact of Information Technology on Labor Productivity - A Field Study," *Decision Support Systems*, 19, 2 (1997), 109-22.

Mukhopadhyay T., S. Rajiv, and K. Srinivasan, "Information technology impact on process output and quality ," *Management Science*, 43, 12 (1997), 1645-59.

Nakamura L. I., "Measuring Inflation in a High-Tech Age," *Business Review (Federal Reserve Bank of Philadelphia)*, 132, 12 (1995), 13-25.

Nelson R. A., T. L. Tanguay, and C. D. Patterson, "A Quality-Adjusted Price Index for Personal Computers," *Journal of Business and Economic Statistics*, 12, 1 (1994), 23-31.

Oliner S. D. and D. E. Sichel, "Computers and Output Growth Revisited: How Big is the Puzzle?," *Brookings Papers on Economic Activity*, 2, (1994), 273-334.

Orlikowski W. J., "Improvising Organizational Transformation Over Time: A Situated Change Perspective," *Information System Research*, 7, 1 (1996), 63-92.

Orlikowski W. J. and J. D. Hofman, "An Improvisational Model for Change Management: The Case of Groupware Technologies," *Sloan Management Review*, 38, 2 (1997), 11-21.

Porter M. E., *Competitive Strategy*. New York, NY: Free Press, 1980.

-----, *Competitive Advantage: Creating and Sustaining Superior Performance*. New York: The Free Press, 1985.

Rao H. R. and B. D. Lynch, "Hedonic Price Analysis of Workstation Attributes," *Communications of the ACM,* 36, 12 (1993), 95-103.

Rao V. S. and S. L. Jarvenpaa, "Computer Support of Groups: Theory-Based Models for GDSS Research," *Management Science,* 37, 10 (1991), 1347-62.

Rifkin J., *The End of Work: The Decline of the Global Labor Force and the Dawn of the Post-Market Era.* New York, NY: G. P. Putnam's Sons, 1995.

Roach S. S., "Services Under Siege - the Restructuring Imperative," *Harvard Business Review,* (1991), 82.

-----, "Best Case Study of All," *Forbes,* 154, 4 (1994a), 27.

-----, "Premier 100: Lessons of the productivity paradox," *Computerworld,* 23, 13 (1994b), 55.

Romer D., "The Productivity Slowdown, Measurement Issues, and Explosion of Computer Power: Comment," *Brookings Papers on Economic Activity,* 2, (1988), 425-8.

Rosen S., "Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition," *Journal of Political Economy,* 82, 1 (1974), 34-55.

Sabyasachi M. and A. K. Chaya, "Analyzing Cost-Effectiveness of Organizations: The Impact of Information Technology Spending," *Journal of Management Information Systems,* 13, 2 (1996), 29-57.

Schmidt R. C., "Managing Delphi Surveys Using Nonparametric Statistical Techniques," *Decision Sciences,* 28, 3 (1997), 763-74.

Sichel D. E., "Computers and Aggregate Economic Growth: An Update," *Business Economics,* 34, 2 (1999), 18-24.

Soe L. L. and M. L. Markus, "Technological or Social Utility? Unraveling Explanations of Email, Vmail and Fax Use," *Information Society,* 9, 3 (1993), 213-36.

Solow R. M., "We'd Better Watch Out," *New York Times Book Review,* (1987), 36.

Strassmann P. A., "Will Big Spending on Computers Guarantee Profitability?," *Datamation,* 43, 2 (1997), 75.

Tapscott D. and A. Caston, *Paradigm Shift: The New Promise of Information Technology.* New York, NY: McGraw-Hill, 1993.

Teng J. T. C. and K. Ramamurthy, "Group Decision Support Systems: Clarifying the Concept and Establishing a Functional Taxonomy," *INFOR,* 31, 3 (1993), 166-85.

Triplett J. E., Concepts of Quality in Input and Output Price Measures: A Resolution of the User Value-Resource Cost Debate. Foss M. F., Editor. *The U.S. National Income and Product Accounts: Selected Topics.* Vol. 47, NBER Studies in Income and Wealth. Chicago, IL: University of Chicago Press, 1983: 269-311.

----, "The Economic Interpretation of Hedonic Methods," *Survey of Current Business,* 66, 1 (1986), 36-40.

----, Hedonic Functions and Hedonic Indexes. Eatwell J., M. Milgate, and P. Newman, eds. *The New Palgrave: A Dictionary of Economics.* Vol. 2. London: MacMillan Press, 1987: 630-4.

----, Price and Technological Change in a Capital Good: A Survey of Research on Computers. Jorgenson D. W. and R. Landau, eds. *Technology and Capital Formation.* Cambridge, MA: MIT Press, 1989: 127-213.

----, Hedonic Methods in Statistical Agency Environments: An Intellectual Biopsy. Berndt E. R. and J. E. Triplett, Editors. *Fifty Years of Economic Measurement: The Jubilee of the Conference on Research in Income and Wealth.* Vol. 54. Chicago, IL: University of Chicago Press, 1990: 207-33.

Waugh F. V., "Quality Factors Influencing Vegetable Prices," *Journal of Farm Economics,* 10, 2 (1928), 185-96.

Weill P., "Strategic Investment in Information Technology: An Empirical Study," *Information Age,* 12, 3 (1990), 141-7.

----, "The Relationship Between Investment in Information Technology and Firm Performance: A Study of the Valve Manufacturing Sector," *Information Systems Research,* 3, 4 (1992), 307-33.

Williams B. K., S. C. Sawyer, and S. E. Hutchinson, *Using Information Technology.* 3rd edition. Boston, MA: McGraw-Hill, 1999.

Appendix 1: The Productivity Paradox

> *...official data show enormous gains in the manufacture of computers, but apparently little productivity improvement in their use.... What has all that computer power being doing, and where is the "black hole" into which all those computers have been disappearing?*
>
> Baily and Gordon (1988), p. 350-351

> *You can see the computer age everywhere but in the productivity statistics.*
>
> Robert M. Solow (1987), p. 36

Motivation

The economic impact of computers, and information technology (IT) in general, has become an issue of significance and controversy. By the mid 1990s, US expenditures on IT exceeded 50% of firms' total yearly investment in equipment.[70] IT investment in 1996 was 2.8% of US GDP, or $505 billion.[71] At the close of the 20th Century, spending on information technology hardware accounts for 57% of all business investment in equipment.[72] The magnitude of IT investment makes its economic payoff, or lack thereof, an important issue for economists and general managers.

However, the level of spending does not fully capture the pervasiveness of IT. Computers and communications technology are *general purpose technologies* that have found applications in every sector of the economy. If large productivity gains are ever to be wrung from IT, its effects could eclipse those of the first two industrial revolutions.

Computers have undergone a sustained period of rapid quality improvement. Since the stages of early commercialisation in 1951, computer processors have declined in (quality-adjusted) price at an average rate of 20-30% per year. Compounded over 45 years, this amounts to an improvement in the price/performance ratio of at least four orders of magnitude. This trend shows no sign of abating in the near future; thus, price declines will continue to expand the range of feasible applications for computer technology.

However, despite the widespread use of and heavy investment in IT, there have apparently been very few positive economic impacts. The "productivity paradox"—the finding that, despite heavy investment in information technology, productivity in the service sector was stagnant throughout the 1980s—was brought to light in the early

---

[70] *The Economist* (1996), p. s13

[71] Strassmann (1997), p. 75

[72] Lohr (1999).

1990's (Roach, 1991). Since then, numerous studies have attempted to gauge the payoff to IT using a number of metrics: accounting profits, share prices, labour productivity, total factor productivity, return on assets (ROA) or equity (ROE), and value-added. Many of these studies have found negative or insignificant returns to investments in information technology, providing support for the "productivity paradox."[73]

Several prominent researchers have expressed concern that IT does not yield productivity improvements. In this camp is MIT economist Paul Krugman, whose position is summarised in *The Economist:*

> Despite hundreds of studies, the dismal scientists remain deeply divided on why the computer revolution has failed to spur productivity. One possible, if depressing, explanation is that there has been no revolution, and that computers are simply not particularly productive. Paul Krugman, an economist at MIT and never one to dodge controversy, argues that recent technological advances are not in the same league as those achieved earlier in this century. Looking back to the 1950s and 1960s, when productivity surged, he points out that changes in technology then affected every aspect of life. In 1945, crossing America by train could take three days, and groceries were bought in mom-and-pop stores; by 1970 the journey from one end of the country to the other took five hours by plane, and groceries came from big, efficient supermarkets. By comparison, he claims, IT has less effect on the average person's life. "Computerised ticketing is a great thing, but a cross-country flight still takes five hours; bar codes and laser scanners are nifty, but a shopper still has to queue at the checkout."[74]

Thomas Landauer, former director of Cognitive Science Research at Bellcore, feels that computer systems and software have been so poorly designed as to make productivity improvements the exception rather than the rule. Indeed, he feels that the entire economy-wide paradox can be blamed on IT:

> How much of the post-1960s slowdown in productivity growth could be due to the failure of computer investments to pay off? ... The numbers fit quite well: up to $30 billion missing new GNP per year, about $30 billion per year worse return on new investments. Indeed the lower yield of IT capital accounts for residual growth failure at the high end of the range of econometric estimates.[75]

Stephen Roach, a senior economist at Morgan Stanley, feels that because the service sector has been relatively sheltered from global competition, IT use by the service sector has not enhanced productivity but has instead contributed to organisational slack (Roach, 1991; Roach, 1994a; Roach, 1994b)Roach, 1994b; Roach, 1994a. He describes the situation in the 1980s:

---

[73] In this paper, the "Productivity Paradox" refers to the inconclusive findings regarding the economic payoff of information technology. The term "Productivity Paradox" has also been used, primarily by economists, to refer to the post-1973 slowdown in growth rates in OECD countries.

[74] *The Economist* (1996), p. s16

[75] Landauer (1995), p. 44-45

> Sheltered from competition by regulation and the lack of foreign players, service companies were becoming more complacent about matters of cost control and were loading up on both workers and machines. The result was a bad case of bloated costs, highlighted by a rapidly growing infrastructure of unproductive information technology.[76]

Regardless of the credibility of any single argument, there is substantial concern in the general business and popular press about the overall productivity of IT. A recent literature survey revealed more than 350 articles in the period 1996-1997 dealing with the productivity paradox.[77] A common thread in the management literature is the fear that the billions invested in IT may have been all but wasted.

If the productivity paradox is important to economists and general managers, it is even more critical to the players in the high technology industry. Computer scientists, information systems (IS) managers, and IS researchers are all confronted with the possibility that their entire discipline is a "black hole." The temptation, of course, is to blame the economists who have conducted these unflattering studies. Roach pokes fun at this reaction:

> Emotions run high at the mere mention of the fabled productivity paradox. Just the hint that computers haven't delivered their long-promised payback has sent shock waves up and down high-tech America. And with good reason. Such a profound challenge goes right to the heart of the supposed miracles of information technology. It must be a measurement problem, the critics say. Surely technology has always been of great value but undoubtedly in ways that are escaping the U.S. government's economic accounting system. Fix the metrics, and presto! The paradox would vanish.[78]

All the news isn't bad, however. The recent, strong figures for aggregate US productivity growth (2.0% per year for 1996-1998), are now causing several prominent economists to re-evaluate their positions. The Nobel laureate economist Robert Solow, discussing the impact of IT on productivity, remarked "My beliefs are shifting on this subject. I am still far from certain. But the story always was that it took a long time for people to use information technology and truly become more efficient. That story sounds a lot more convincing today than it did a year or two ago."[79] In contrast to his previous work, Daniel Sichel, senior economist with the Federal Reserve, in a recent study finds "a striking step-up in the contribution of computers to output growth."[80]

However, it's not clear whether the findings are, in fact, due to greater benefits emerging from IT or from a generally more robust business environment. Paul Strassman, former CIO for Xerox and the Pentagon, continues to advocate the position that investments in computers have been, by and large, "squandered." He comments: "The explanation for

---

[76] Roach (1994b), p. 55

[77] This search was conducted in the current news (CURNWS) file of Lexis-Nexis, and took only a few seconds to retrieve the hits. Ironically, such a search would have not have been feasible without information technology.

[78] Roach (1994b), p. 55

[79] As quoted in Lohr (1999).

[80] Sichel (1999), p. 18.

the productivity improvement is interest rates, not information technology. The hero here is not Bill Gates, it's Alan Greenspan."[81] The ever-cautious Alan Greenspan, however, disagrees, stating recently:

> I have hypothesised before this group on several occasions that the synergies that have developed, especially among the microprocessor, the laser, fibre-optics and satellite technologies, have dramatically raised the potential rates of return, not only on new telecommunications investments, but more broadly on many types of equipment that embody or utilise the newer technologies.
>
> The newest innovations, which we label information technologies, have begun to alter the manner in which we do business and create value, often in ways not readily foreseeable even five years ago.
>
> I do not say that we are in a new era, because I have experienced too many alleged new eras in my lifetime that have come and gone. We are far more likely, instead, to be experiencing a structural shift similar to those that have visited our economy from time to time in the past. These shifts can have profound effects, often overriding conventional economic patterns for a number of years, before those patterns begin to show through again in the longer term.
>
> ... The evidence nonetheless, for a technology-driven rise in the prospective rate of return on new capital, and an associated acceleration in labour productivity is compelling, if not conclusive.[82]

Thus, the debate continues. While IS practitioners and researchers are unlikely to agree that investment in information technology has been wasted, they have had to proceed on faith. Thus far, they have not been able to definitively demonstrate the benefits of IT in any form other than with anecdotes. The "measurement problems" that Roach mentions are a serious issue, affecting our ability to accurately measure either investment in IT or its output. These measurement problems exist at various levels of analysis: the individual worker, the workgroup, the firm, the industry, and the economy. The issue of the impact of IT (in terms of productivity or any other payoff) has not been resolved at any of these levels. Much work is being done, and much work remains to be done—the economic impact of IT is a vibrant research area.

In order to frame the research problem addressed in the dissertation, this appendix presents an in-depth review of prior research assessing the economic impacts of investment in IT as well as a discussion of the promulgated explanations for the productivity paradox. The appendix concludes with a summary of the central themes in these discussions, and provides a description of how the dissertation addresses one of the key outstanding problems in this area: the measurement of IT as an input.

---

[81] Also as quoted in Lohr (1999).

[82] Greenspan (1999)

Background: Research on the Productivity Paradox

Numerous explanations have been advanced to account for the productivity paradox. Some researchers argue that the failure to demonstrate productivity is due to inadequate research tools or methods, while others argue that there are simply no productivity gains to be had from IT. The most frequently proposed explanations are variations on five themes:

1. **Mismeasurement:** Problems exist in the measurement of IT as an input to production, as well as of the output of firms in the service sector, the largest user of IT. Perhaps the lack of measured productivity impacts is simply due to inadequate or inaccurate measures.

2. **Lags:** There is limited empirical support for the finding that the benefits of IT investment lag spending by at least two years. In addition, the effective use of a new general-purpose technology may take decades to unfold. Thus, the lack of productivity to date may be due to a delay, or part of a learning process.

3. **Redistribution:** Perhaps investment in IT creates value, but that value is "competed away" and ends up as an unpriced, and hence unmeasured benefit to the consumer. Thus, the firms making the IT investment do not appear to reap any benefit—the productivity paradox.

4. **IT Does Not Improve Productivity:** Perhaps the simplest explanation of the productivity paradox is that IT does not, in fact, contribute to increased productivity or economic growth.

5. **There is No Productivity Paradox:** Perhaps there is no productivity paradox. Even though spending on IT is large, the stock of IT capital may be too small to make a measurable contribution to productivity.

Each of these proposed explanations will be discussed following a survey of prior research assessing the productivity of IT investments.

Levels of Analysis

The question of whether, and how much, information technology contributes to "productivity" can only be meaningfully addressed by defining at what level productivity will be measured. For this discussion, we consider five levels at which productivity measures are meaningful: the individual, the workgroup, the firm, an industry, and the economy.

While these levels are certainly inter-related, it is not automatic that a productivity improvement at any lower level will filter up to higher levels. For example, a typist may improve his individual productivity in letter preparation by the adopting a word-processing system; however, if he spends the time saved playing solitaire on his PC or "chatting" with friends over the Internet, then measurement of the firm's productivity will not show the increase. Likewise, it may be possible for one firm to increase its productivity and profit by passing some of its costs onto other members of its supply chain, e.g., suppliers, through threat, coercion, or other application of its bargaining power. However, when these costs are taken into account in measuring the overall productivity in the industry, there will be no net gain.

The Individual

In its earliest applications, IT was a substitute for blue-collar work and a compliment for white collar work: with the installation of a computer system, clerks were replaced with (a smaller number of) computer operators. Recently, however, IT has also become a substitute for white-collar work. The possibility of the "end of work" has been raised as a consequence of mass replacement of service workers by information technology (Rifkin, 1995).

One of the chief problems in measuring the impact of IT is that it changes the quality of the work done. When a new machine is installed in a factory, it is typically fairly easy to assess its impact because there exist comparable physical units of output: the machine (plus operators) produces x widgets per day, or improves the yield of process y by z%. The adoption of a word processor by a typist may increase the number of letters produced per day in certain applications, such as legal documents that contain standardised paragraphs. Also likely, however, is an improvement in the quality of the letter: freedom from spelling errors, block-justified text, use of multiple fonts or eye-pleasing graphics. While this improved quality may be of economic value, it is unlikely to be captured by standard productivity measures, such as letters-per-day. Similarly, a manager who uses a spreadsheet to conduct a sensitivity analysis may make "better" decisions, but be slower in doing so. On the criterion of decisions-per-day, his productivity has declined. Obviously, this is an inadequate metric; ideally, his productivity would be measured in terms of the economic impact of his decisions for the firm. However, where outputs are services derived from individuals, the state-of-the-art in output metrics is, unfortunately, far from ideal. These difficulties in measuring output make it difficult to construct valid assessments of the impact of computers on individual productivity.

Perhaps due to the difficulties described above, there have been relatively few studies that directly measured individual productivity pre- and post-computerisation. Landauer (1995), discusses a small number of studies: a study of word processors finds that they do not speed up the creation of letters; a study of text searching finds that a new user-interface can significantly improve access time and accuracy. The small number of studies at this level of analysis do not well represent the domain of applications aimed at individual productivity, and hence leave the area largely unresolved.

Recent econometric work has suggested that there may exist a wage premium associated with using a computer at work. If a wage premium does exist, it is hypothesised that it allows the worker to capture at least a portion of the productivity improvement that comes from using a computer at work (Krueger, 1993). However, this finding was been strongly disputed in DiNardo and Pische (1996), which, using similar data and methods, finds a wage premium for using a pencil at work or sitting at work. The authors argue that the variables that measure computer use (and pencil use) are likely picking up unobserved heterogeneity among workers, thereby serving as a proxy for worker ability or differentiating between white-collar and blue-collar workers.

A recent study examined individuals' adoption of three technological modes of communication: email, voice-mail, and fax (Soe and Markus, 1993). Interestingly, it was found that adoption of a particular technology had less to do with the nature of work being performed than it did with an individual's assessment of the technology's social utility. This finding supports the argument made below that technologies may be used for their intrinsic utility in addition to (or instead of) their productive capacity.

Finally, IT can provide economic value to an employee without an impact on the employer. For example, IT enables workers to *telecommute*, i.e., to work at home by remotely accessing the computer system of their employer. Provided that the employee works as hard and for as many hours at home as she would in the office, this arrangement will not provide any productivity or other gains to the employer. Telecommuting, however, provides economic value to the employee, in terms of time saved in commuting. Lipsey (1990) comments on these unmeasured sources of value, and argues that they should be taken into account in the system of national accounts.

The Workgroup

Information technology is affecting the ways that work and organisations are structured. One recent transition has been from work being managed by a tightly organised hierarchy to being the responsibility of *business teams* or *workgroups* whose membership cuts across organisational boundaries (Tapscott and Caston, 1993). The support of these teams requires extensive communication and access to shared information resources, made possible through the use of PCs, networks, and *groupware*, which is software designed to support collaborative work (e.g., Lotus Notes).[83]

Because of its reliance on network technology, the shift to workgroups is a relatively recent phenomenon. Orlikowski (1996), as well as Orlikowski and Hofman (1997), documents the adoption of Lotus Notes and the resulting, emergent, organisational adaptations within one firm. Hammer and Champy (1993) describes two successes that have become classics within the BPR literature: Ford's accounts payable department and IBM's credit division.

Information technology has also been applied to improving the quality of decisions made by groups; this technology is known as *group decision support systems* (GDSS). This arrangement represents a challenge for IT that is not captured at the individual level: supporting a group of people to work together effectively. The literature on GDSS is large; summary frameworks are presented in Rao and Jarvenpaa (1991) and in Teng and Ramamurthy (1993).

The workgroup level is an increasingly important level of analysis in terms of productivity and economic performance. However, productivity measures for workgroups or teams have not been formalised, which makes examining the impact of IT difficult. The measurement difficulties are confounded by the change in organisational form that typically accompanies the installation of a groupwork IT system: a pre-post comparison would be comparing the work of individuals to the work of teams utilising technology. Even if the productivity at both levels of analysis could be accurately measured, it would

---

[83] The use of information technology to support new methods for accomplishing business processes has been dubbed *business process reengineering* (BPR). BPR is discussed more fully in below.

not be possible to separate the effects of IT from the effects of team-based work. To date, case studies remain the best research method applied at this level of analysis, but are unfortunately unable to use econometric methods to quantify the effects of IT spending.

The Firm

The majority of research on the economic impact of information technology has been performed at the firm level of analysis. Key to a firm-level analysis are good measures of IT spending or capital stock, as well as good measures of firm output. Of these two measures, the latter is quite easily obtained for publicly traded firms; databases such as Compustat provide yearly data on firm performance and key economic variables. Reliable measures of IT spending have been much more difficult to obtain, for two reasons. First, accurate measurement of the total IT spending within a firm requires information on IT spending by the firm's central IS department, as well as all spending on IT in "user" departments. Identifying and combining these distinct budgets is difficult. Second, an apparently significant portion of IT costs may not be identified as IT costs; examples include IS personnel, infrastructure such as communications networks and telephone exchanges, software, and the time of the computer "guru" down the hall, who helps when the printer doesn't work, but at the expense of his own work.

One source for data on IT spending is the Computer Intelligence Corporation, a division of Ziff-Davis Publishing. Computer Intelligence (CI) performs tens of thousands of "site visits" a month, during which the IT resources of a business unit are catalogued in detail. This data is combined to produce a "profile" of a company that includes data on the number, brand, and model of micro-, mini-, and mainframe computers, as well as peripherals such as networks, printers, fax machines, telephone exchanges, etc. Market value of the firm's IT resources are then estimated based on current prices. The data collection method—physical inspection—makes this data source more reliable than those based on other methods, such as telephone surveys. To date, only two studies have made use of the CI data. Lichtenberg (1995) is based on a ranking of firm spending on IT (derived from CI data as published in Computerworld magazine) to estimate firm spending. Lehr and Lichtenberg (1997) makes use of three years worth of CI data (1986, 1991, and 1993).

Other private data sources, such as the International Data Group's (IDG) annual survey of Fortune 500 companies, are based on less rigorous methods. The IDG survey is telephone-based, and includes questions that will require a significant amount of "estimation" on the part of respondents. An example is the item "What will be the approximate current value of all major processors, based on current resale of market value? Include mainframes, minicomputers, and supercomputers, both owned and leased systems. Do NOT include personal computers."[84] A comparison of the Compustat and the CI data (as published in *Computerworld* magazine) concluded that the CI data are more reliable (Lichtenberg, 1995).

The firm has much to offer as the unit of analysis. The microeconomic theory of production is based on the firm. The theory of production provides the framework of the production function by which to estimate the impacts of the various factors of production.

---

[84] See Appendix A of Brynjolfsson and Hitt (1996), available from the authors.

However, the firm may be problematic as a unit of analysis of the impacts of IT, for a number of reasons:

- The sample of firms for which the necessary data (IT spending and firm output) is available is anything but random, so an epidemiological study is not possible. Fortune 500 or Fortune 1000 firms have typically been the sample for which firm-level data on IT are available. Because these firms are the largest in the economy, and larger firms have been shown to be more intensive users of IT, this sample may misrepresent the impact of IT in the average firm.[85] However, accounting for a significant proportion of the Fortune 500 has the advantage of representing a significant proportion of the US economy.

- Demonstrating causality is problematic: does IT cause firm profits, or do firm profits permit spending on IT? With data for a sufficient number of years, this problem can be addressed through an analysis of lagged effects. Firm-level regressions that demonstrate positive returns to IT (e.g., Brynjolfsson and Hitt, 1993) have been critiqued (see DiNardo and Pische, 1996) with the argument that the positive returns to IT spending may be an artefact of unobserved heterogeneity between firms. Effective use of IT could be a proxy for another variable, such as effective management. There is evidence to at least partially support this assertion: when firm effects were included in the economic model in Brynjolfsson and Hitt (1995) and in Lichtenberg (1995), firm effects were found to account for about 50% of IT's returns. Weill (1992) uses retrospective data for six years' spending on IT, testing for and finding a "circular" relationship, i.e., the answer to causality question is "both."

- Firm output measures, especially in the service sector, can be problematic or inaccurate. Profit or other measures of firm performance may not capture productivity improvements if they go unpriced or appear as unaccounted-for quality improvements. (See the redistribution argument below.)

Having discussed the implications of using the firm as the level of analysis, the previous research at this level will be reviewed. First, research using solely the microeconomic theory of production will be addressed. Second, the approach of "business value modelling" will be introduced and reviewed.

Production Function Estimation

An early study used the survey methodology to examine the relationship between "computerisation" and firm performance (Cron and Sobol, 1983). The primary finding was that extensive use of computers was associated with both very high and very low levels of performance, operationalised as sales growth, pre-tax profits, and ROA. Interestingly, for firms that made high use of IT, large firms were among the highest performers, and small firms the lowest performers, causing the authors to speculate that IT was helping to reinforce economies of scale.

[85] Larger firms have been shown to be more intensive users of IT, in terms of IT spending as a proportion of revenue. See, for example, Sabyasachi and Chaya (1996).

Morrison and Berndt (1991) and Berndt and Morrison (1995) examine manufacturing industries. The 1991 paper uses a "parameter rich specification" of the production function, and estimates results for the period 1952-86. The results are mixed, but on balance indicate that the marginal cost of IT exceeds its marginal benefit, indicative of over-investment in IT. Interestingly, in the 1995 paper, the authors use a much more general specification (examining correlations) for the 1968-86 period. They find weak evidence that IT increases profits, but decreases productivity. The choice to use manufacturing industries has been criticised in Lichtenberg (1995), which notes that manufacturing firms make relatively little use IT, so the effects of IT investment would be comparatively small in magnitude and therefore difficult to detect.

The Management Productivity and Information Technology (MPIT) database, a subsection of the PIMS (Profit Impact of Market Strategy) data set, was used for early work on IT impacts (Loveman, 1994). MPIT contains data on 60 business units from 20 firms, largely fortune 500 manufacturing firms, for the years 1978-84. "In this sample, there is no evidence of strong productivity gains from IT investments. The implied shadow value of IT does not favour further investment for the period covered by the data, and any implied rate of return is very low."[86] These early, dismal results were influential in shaping the "productivity paradox" debate to come. However, this data set has recently been re-examined, with significantly different results (Barua and Lee, 1997, discussed below).

MIT IS researcher Erik Brynjolfsson and then doctoral student Lorin Hitt perform a number of analyses using the IDG database for 1988-92 (Brynjolfsson and Hitt, 1993; Hitt and Brynjolfsson, 1994; Brynjolfsson and Hitt, 1995; Brynjolfsson and Hitt, 1996). The '93, '94, and '96 versions of the paper all use a Cobb-Douglas production function, and find evidence of "excess returns," on the order of 60%, to investment in IT capital.[87] Because these were among the first studies demonstrating excess returns, they have been a target for criticism. For example Landauer (1995), disputes their choice of price index (Gordon, 1990) as being too large.[88] He also notes the causality and sampling problems discussed above. The causality question is addressed in a subsequent analysis (Brynjolfsson and Hitt, 1995). This paper tests for the presence of firm effects, finding not only that they are significant, but that they also account for about 50% of the earlier-cited excess returns.[89] This paper also tests the less restrictive translog production function, and finds that the restrictions required by the Cobb-Douglas function are rejected. The translog specification again reduces the excess returns to IT, in this instance by a further 20%.

In addition, Lichtenberg (1995) indicates that the IDG data set may not be reliable, and finds fault with Brynjolfsson and Hitt's hypothesis test for excess returns. Lichtenberg contends that since their test is based on gross, rather than net, returns, it fails to

---

[86] Loveman (1994), p. 94

[87] Note that these are estimates of gross returns, not net of investment costs in IT. Given the high depreciation rates of IT hardware, the net return will naturally be much lower.

[88] Note that Gordon's price index ends in 1984, four years before the IDG data set begins.

[89] As noted in their 1996 paper, the presence of firm effects would render invalid the use of once-lagged variables as instruments to correct for autocorrelation. Thus, questions are now raised regarding the validity of their earlier findings.

account for the rapid price declines that computers suffer.[90] This asset depreciation causes the ratio of rental price to purchase price for computer capital to be greater by a factor of six than for other types of capital. With the least restrictive specification (translog production function with firm effects) and the Lichtenberg hypothesis test, the hypothesis of "excess returns" to information technology will likely be rejected.

Lichtenberg (1995) does find evidence of excess returns to spending on IT and IS labour; the only shortcoming being his data set, which only covers four years (1988-91). He finds that one IS employee produced an output equivalent to six non-IS employees. Lehr and Lichtenberg (1997) finds strong evidence of excess returns to IT, which appear to have peaked in 1986 or 1987, and have since been declining. This work combines two data sets, and samples the period 1973-93, but requires some contortion to turn data on IT spending into IT assets and to match the two data sets. Because the data are not year-to-year, the authors cannot test for lagged relationships. Due to the reliability of the two data sources (Computer Intelligence and the Census Bureau's Enterprise and Auxiliary Establishment Surveys), this work appears to be strong evidence of excess returns to IT. The chief limitation of this work is that it only samples three years within the 20-year period.

The UK engineering industry was the basis for examining the effects of five types of IT hardware on firm production (Kwon and Stoneman, 1995). For the period 1981-90, the overall results indicate that IT adoption had a positive impact on output and productivity, although the "net" returns are not explored. Looking at the five individual technologies, three were found to have positive impact (numerically controlled machine tools, coated carbide tools, and computers for administrative use), one was insignificant (computerised numerically controlled machine tools), and one was significantly negative (the vaguely titled class of "microprocessors"). Unfortunately, the authors do not provide insight into their curiously mixed results.

Sabyasachi and Chaya (1996) examines, once again, the published *Computerworld* data for the period 1988-92. The findings suggest that IT lowers the average cost per unit of output, but does not affect labour productivity. These results lead to the hypothesis that IT reduces co-ordination and control costs, but increases overhead costs.

The subject of the impact of IT on organisational form has also been addressed (Brynjolfsson et al., 1994). This paper constructs a theoretical framework using the Grossman-Hart-Moore incomplete contracts approach to examine the effects of the ownership of information assets. This framework is tested empirically using the Bureau of Economic Analysis (BEA) data on Office, Computing, and Accounting Machinery (OCAM) to assess changes in firm size due to IT. The results suggest that IT is associated with reductions in all measures of firm size, suggesting that IT permits outsourcing of non-core tasks. The results of IT spending are found to lag behind spending; the effects of IT on organisational form are strongest two to three years after investment.

The early, negative findings from the MPIT data set have been revisited in Barua and Lee (1997). In this paper, the authors make two methodological improvements in the

---

[90] In this dissertation, the term "price declines" is used in place of the unwieldy (and self-contradictory) economic term "negative asset price appreciation."

analysis of the data. First, they note that microeconomic production theory is based on firms choosing inputs to maximise profit (or, equivalently, minimise costs). Thus, simply estimating a production function treats the input variables (e.g., levels of labour, capital, and IT capital) as exogenous, when they are in fact endogenous to the firm's choice. This approach, they assert "...is not consistent with the theoretical foundation of production economics."[91] Thus, instead of estimating a single production function, the authors simultaneously estimate a system of equations corresponding to the first-order conditions for profit maximisation. The results of the "endogenous specification" are qualitatively different from the typical production-function specification, and are more consistent with economic theory, in that they find that all inputs are positive and statistically significant contributors to output. The authors apply a Hausman specification test to verify that their endogenous specification is preferred to the exogenous specification. Second, the authors apply a different input deflator to the IT-capital data than was originally used (Loveman, 1994). The authors discuss this choice:

> In replicating Loveman's results, we discovered a striking difference between the IT deflators employed in our and Loveman's studies. Loveman used the BEA quality-adjusted computer price index to deflate IT investment. This choice is appropriate if IT consisted only of computers. However, the MPIT definition of IT corresponds well with the BEA category Information Processing and Related Equipment. ... Note that computers are included only in the subcategory Computers and Peripheral Equipment. As we would expect based on these subcategories, there are major differences between the IPRE deflator we used in our study and the price index of computers. ... Thus, using the computer price index under the assumption of IT as consisting only of computers results in too much deflation. ... We take the position that, because the operational definition of IT in the MPIT data set corresponds to the IPRE category, it would be natural to choose the IPRE deflator (in spite of the well-documented limitations of any capital input deflator) rather than a computer price index.[92]

The authors conclude that the choice of the appropriate input deflator for IT is critical to the estimated results: "Further, we provide empirical evidence that the choice of the input deflator led to negative results in an important prior study [Loveman 1994]."[93]

Business Value Modelling

The concept of "business value modelling" (BVM) was developed over a number of years and a number of working papers, but was recently formalised (Barua et al., 1995). The approach of BVM is based on the hypotheses that the impacts of IT may be impossible to accurately detect using the approach of production function estimation.

> By attempting to relate IT expenditures directly to output variables at the level of the firm (such as market share) through a microeconomic production function, the intermediate processes through which IT impacts

---

[91] Barua and Lee (1997), p. 149

[92] Barua and Lee (1997), p. 159-160

[93] Barua and Lee (1997), p. 162

> arise are ignored. There has been a growing concern ... that the effects of IT on enterprise level performance can be identified only through "a web of intermediate level contributions."[94]

Thus, the authors suggest a two-stage approach to assessing IT impacts.

> These studies indicate the need for more process-oriented models instead of traditional "black box" approaches. Our basic thesis is that primary economic impacts or contributions (to performance) of information technologies (if any) can be measured at lower operational levels in an enterprise, at or near the site where the technology is implemented. To capture these impacts, measurements should be taken in the organisation where the potential for first-order effects exists. These effects may then be traced through a chain of relationships within the organisational hierarchy to reveal higher order impacts (if any) on enterprise performance.[95]

The authors apply this two-stage approach to the MPIT data set. The data set is decomposed by application area, based on Porter's value chain (Porter, 1985). The first stage of analysis is to identify the direct impact of IT projects. For example, variables such as capacity utilisation and inventory turnover are regressands in models, based on the production process, that verify the determinants of these intermediate variables. The second stage of the analysis verifies that these intermediate variables have an impact on final economic outcomes such as market share and ROA. Through this chain of causality, the authors demonstrate that IT investments, via intermediate variables, do, in fact, affect final economic performance.

Although they predate the seminal paper on BVM, two studies of firms in the valve manufacturing industry apply part of the approach of business value modelling (Weill, 1990; Weill, 1992). These studies are among the few that classify IT spending by objective: *strategic*, which is aimed at gaining market share; *informational*, which provides information to support management and decision-making; and *transactional*, which supports transaction processing. Of these three types of spending, only transactional was found to be positively associated with economic performance. Total spending (i.e., the sum of strategic, informational, and transactional) was not significantly correlated with economic performance. The construct *conversion effectiveness*, a measure of IT competence, was found to be useful in predicting a firm's ability to transform investment to payoff. As mentioned above, Weill also finds evidence of a circular relationship between firm performance and IT spending in which both cause the other. His findings on conversion effectiveness are strong support for including firm effects in any model of IT investment. However, Weill's findings highlight another potential problem with the firm as a unit of analysis: it may aggregate too many IS activities to permit a meaningful analysis, and the payoffs of certain types of IS projects may be lost. This finding supports the approach of decomposing IT projects at least to the level of application area, as recommended in Barua et al., (1995).

---

[94] Barua, Kriebel, et al. (1995), p. 6

[95] Barua, Kriebel, et al. (1995), p. 6-7

Also predating the BVM paper is a study based on the hypothesis that managers act so as to maximise the value of the firm (Dos Santos et al., 1993). Using event study methodology, the authors investigate the effect that a firm's announcement of an IT project has on the market value of that firm. Using the capital asset pricing model, firm-specific parameters are estimated using 200 daily observations prior to the IT announcement. Following the announcement, deviations of realised returns from normal returns are used to estimate changes in the market value of the firm, attributed to investors' reaction to the announcement. For the overall sample of 97 firms, the estimate of excess returns due to the IT project are non-significant, indicating that IT projects have a NPV of zero. However, one subset of firms, those announcing "innovative" IT investments, did show a positive and statistically significant excess return following the announcement.

As part of the stream of literature that developed and refined the approach of BVM, the case of inventory management was examined (Mukhopadhyay and Cooper, 1993). The authors characterise "information" as consisting of two attributes: accuracy (the extent to which a description is in accord with reality) and coverage (the extent to which the description represents the relevant parts of reality, broken down further into five areas, including timeliness). The authors propose a "net contribution function" [Net Contribution = f(decision coverage, decision accuracy)]. They suggest that by estimating the net contribution function, managers can evaluate MIS systems by the value they create through their accuracy and coverage. In the context of inventory management, they first derive an analytical solution and then examine an empirical case: a paint factory from which a six-year series of data on inventory is fit to a normal demand function and for which a production function is fit to simulated data. The result is a framework to assess the value of improvements in information quality or coverage in the inventory context. This detailed, quantitative approach works well in the context of inventory management (for which the consequences of information accuracy and timeliness are relatively easy to quantify) and other "programmed" decision environments, but is not applicable to decisions for which the value of information cannot be clearly quantified.

The approach of BVM is exemplified in a detailed longitudinal study of the introduction of electronic data interchange (EDI) at Chrysler (Mukhopadhyay et al., 1995). Using electronic records from nine factories covering the period 1981-1990, the impact of EDI is modelled. The dependent variables examined included inventory holding cost, obsolete inventory cost, transportation cost, and premium freight costs. Complicating the analysis are the numerous changes in process and product that occur over the time period; these complications force the authors to control for the effects of a number of moderating variables: production volume, parts variety, new part introductions, and the level of part changes within vehicles. Overall, it is estimated that EDI saves approximately $60 per vehicle produced due to improved information flows. Accounting for reduced document preparation and handling costs yields and additional savings estimated at approximately $40. Through detailed modelling of the direct impacts of EDI and accounting for confounding factors, the authors are able to obtain excellent insights into the impact of EDI over time at Chrysler. Unfortunately, the authors do not discuss the costs associated with adopting and maintaining the EDI initiative, so the net returns cannot be assessed.

Applying the approach of studying a single technology at a single firm over time, two studies examine the toll collection system on the New Jersey Turnpike and the use of optical character recognition at sorting sites of the US Postal Service (Mukhopadhyay et al., 1997; Mukhopadhyay et al., 1997). Again, the insightful, detailed approach not only reveals overall positive impacts of IT, but also reveals the nuances of the production process and identifies why IT does (and in some cases, does not) yield process improvements.

Recent work has investigated whether the composition of the workforce affects the returns realised from IT investment (Francalanci and Galal, 1998). Using data from 52 US life insurance firms over the period 1986-1995, the authors show that investment in IT is associated with improved productivity, provided that it is associated with either or both of: (a) a reduction in clerical and professional staff, and (b) an increase in managerial staff.

The Firm: Summary

While controversial, the early, pioneering work on firm-level economic effects has been valuable. Our understanding of methodological issues has been sharpened, and researchers are now in a position to attempt a "best practice" research program, which would include:

- Good time series data on inputs to production, including reliable measures of IT purchases (e.g., from Computer Intelligence), as well as of real output;
- The appropriate hypothesis tests of net returns to IT spending;
- Flexible specifications (e.g., the translog production function) that include firm effects;
- An appropriate and current price index for computers (for estimating the flow of services available from IT purchases);
- Opening the black box of the firm to examine complements to IT spending. For example, data on type of IT spending (e.g., the informational, transactional, strategic breakdown of Weill, 1992) as well as "conversion effectiveness" or other measure of IT competence permit a more accurate assessment of the return to IT investment.

An Industry

The industry level is an appropriate and interesting level of analysis for assessing IT (productivity) impacts. For this dissertation, the "industry-level" is taken to mean (a sample of) firms at all levels of the value chain within the industry. As mentioned above, some practices can allow firms to shift costs within the supply chain; for example, just-in-time (JIT) inventory may allow manufacturers to pass inventory costs on to suppliers. A firm-level analysis will miss such cost transfers, and may falsely assign too much or too little benefit to information technology. On the other hand, IT can also be used to support industry-wide initiatives that are to the benefit of all players. The continuous replenishment process (CRP), typically implemented using EDI or other inter-organisational system (IOS), is one such example. Again, the industry level of analysis is needed to capture all the effects of IT.

Some of the firm-level studies of IT productivity have also addressed the industry level by categorising their sample of firms by industry and comparing the payoff to firms across industry groups (Morrison and Berndt, 1991; Brynjolfsson and Hitt, 1993; Berndt and Morrison, 1995; Brynjolfsson and Hitt, 1996). However, while these analyses *included* firms from a number of industries, they were not constructed so as to *measure the entire value chain* within an industry. Thus, these are not industry-level studies, as the term is used in this paper.

While measures of the real output of service industries (the heaviest users of IT) are notoriously poor, this problem may be somewhat alleviated at the industry level, at which accounting identities will hold—the output of one level in the value chain is the input to the next. However, these identities are already taken into account in the system of national accounts. Unfortunately, the measurement of IT as an input by government sources is also problematic: BEA's OCAM lumps computers in with other office machinery, and there was no price indexing done prior to 1985.

The industry level of analysis is promising and all-but untouched. However, the measurement problems for an entire industry are daunting. It may be feasible to locate an industry with more accessible data (either due to a small number of players, or a strong industry association) for empirical analysis. Likewise, there is room for theoretical modelling of the effects of IT on an industry: the effects of CRP on the grocery industry would be an interesting starting point.

The Economy

The level of the entire economy is perhaps the most difficult measurement problem. Given the level of aggregation and small size of the IT capital stock in relation to the overall economy, it may be difficult to measure the impact of IT.[96]

One approach would be to use Leontief Input-Output modelling to calculate factor shares. However, the construction of official data (e.g., Statistics Canada) entails considerable assumptions and is unfortunately performed at a level of aggregation that likely renders IT's role in the economy immeasurable. Leontief and Duchin (1986) took the approach of examining factor shares over time and projecting trends into the future. Using these estimates of future factor shares and demand levels, input-output modelling was used to assess the impact of automation on workers. A more sophisticated and recently feasible approach to conduct the same analysis is to construct a computational general equilibrium model. However, as numerical modelling is essentially a method with zero degrees of freedom, it produces estimates that do not have statistical properties (e.g., a standard deviation or a confidence interval) and are thus difficult to interpret.

Landauer (1995) blamed the entire post-1973 slowdown in productivity growth on wasted spending on IT. Recent work on the CPI has concluded that there is a significant upward bias (1.4-1.7%), which would all but explain the economy-level productivity paradox (Nakamura, 1995).

---

[96] Estimates put computer hardware at about 2% of property, plant, and equipment (Oliner and Sichel, 1994), but *The Economist* (1996) puts the figure at 12% when software and telecommunications infrastructure are included.

While there may be work to be done in this area, it is also being intensively pursued by statistical agencies and economists. Thus, this level of analysis does not appear to be particularly ripe for a contribution by IS researchers.

Candidate Explanations for the Productivity Paradox

The productivity paradox can be posed in two complementary ways: (i) Why have firms, governments, and individuals spent so much money on computers when there is no demonstrated productivity payoff? (ii) Why have we been unable to measure the productivity payoff of the billions of dollars invested in computing capital?

Both questions are leading; (i) suggests that computers do not improve productivity, and that, for some reason, otherwise rational individuals have wasted billions of dollars on them, whereas (ii) suggests that computers do, in fact, boost productivity, but our measurement instruments are not capable of capturing this result.

This section discusses five classes of explanations that have been proposed for the productivity paradox. The first three (mismeasurement, lags, and redistribution) are variations on the mismeasurement theme in (ii). The fourth discusses the arguments supporting the assertion that computers do not improve productivity (i). The last takes the position that there is no paradox.

Mismeasurement

Of the two cases described above, case (ii) is much more plausible, in that it only requires that our measurement methods be less than perfect. Indeed, mismeasurement is perhaps the leading candidate as an explanation of the productivity paradox. To accurately assess the contributions of IT to productivity, accurate measures of all inputs, including IT, and outputs are required.

Both input and output measures must account for changes in quality and prices in order to keep the units of measurement equivalent. For example, if a factory producing widgets implements a process innovation such that widgets now last twice as long, then the factory has increased its output in real terms. This increase in real output should be captured whether or not the factory receives higher prices for the new-and-improved widgets. Typically, this adjustment is done by applying a *price index* to the nominal value of the measures. The price index relates the observed price of the input or output to its quality, and is scaled so as to keep "real" prices constant in terms of quality.

With the case of information technology, however, there is evidence of problems with both sets of measures. Paul David, an economic historian at Stanford, argues that the introduction of a new general-purpose technology makes the measurement of output a difficult problem. From his discussion of the productivity slowdown following the development of the electric dynamo at the end of the 19th century:

> A somewhat different class of considerations also holds part of the explanation for the sluggish growth of productivity in the United States prior to the 1920s. These have to do more with the deficiencies of the conventional productivity measures, which are especially problematic in treating the new kinds of products and process applications that tend to be bound for an emergent general purpose technology during the initial

> phases of its development. Here, too, the story of the dynamo revolution holds noteworthy precedents for some of the problems frequently mentioned today in connection with the suspected impact of the computer: 1) unmeasured quality changes associated with the introduction of novel commodities; and 2) the particular bias of the new technology toward expanding production of categories of goods and services that previously were not being recorded in the national income accounts.[97]

Recently, a number of economists have argued that there is a significant bias in the Consumer Price Index (CPI), the which aims to measure the cost of a constant basket of goods and services over time. Apparently the CPI has been overstating inflation for at least the past decade. Thus, US economic performance, including economic and productivity growth have been significantly better than previously believed (Nakamura, 1995; Gordon, 1996; Diewert, 1996). While these papers identify several sources for the bias in the CPI, three of these sources are at least partially attributable to IT.

Outlet substitution bias occurs when consumers shift their purchases from a high-cost outlet to a low-cost outlet for the same good. Consumers have been flocking to superstores such as Price Club, Wal-Mart, and Costco, but the price declines that consumers enjoy go unmeasured due to the strict definition of a "good" for the purposes of the CPI: a specific product purchased at a specific location. Estimates of this bias place it in the range of .25% to .4% per year in recent years.[98] Of the sources associated with IT, this source is perhaps least directly attributable to IT. However, the crucial nature of IT and EDI in the operation of these low-cost retailers has been well-documented (Bradley and Foley, 1994).

Quality adjustment bias occurs when a new variety of a product is introduced that replaces an older variety. If the new variety is "better" on some attribute, it reflects a quality improvement. After two or more periods, the new product is included in the price index, but the decline in price that occurs between the old and new variety is not taken into account.

New goods bias occurs when the consumers' choice sets expands rapidly, as it has in the last decade. Again, traditional index number theory does not account for the expansion of the consumers' choice sets (Diewert, 1987). The combined effect of the quality adjustment bias and the new goods bias has been estimated at between .35% and .6% per year in recent years. These last two sources of bias are exactly those described by David above. Information technology has played a significant roll in improving the quality of goods and services, as well as enabling the introduction of new goods and services.

After defending their productivity statistics for years, the BEA and the Bureau of Labour Statistics (BLS) have recently acknowledged that they may have been understating productivity growth (Dean, 1999; Eldridge, 1999). While there is debate about the magnitude of the bias in the CPI, the acknowledgement of its existence is leading to new methods that aim to reduce or eliminate these biases. Note that if the CPI has been

---

[97] David, 1990, pp. 358

[98] The estimated magnitudes of these biases are taken from Diewert (1996).

overstating inflation by, say, 1% per year, it does not follow directly that productivity growth has thus been understated by the same 1% per year. The CPI is only used in computing a portion of the BLS productivity measures (estimated at 57 percent), and thus any biases in the CPI will only affect a portion of the productivity calculations (Eldridge, 1999).

While these sources of bias in the CPI are clearly important as a possible explanation of the productivity paradox at the economy level, they also have an impact at firm level analyses. The problems of accounting for quality change in the CPI are also present in measuring the output of firms (and industries). When IT investment is used to improve the quality of a firm's output in some way (e.g., faster delivery, more customisation, better service, fewer stock-outs) or to increase product variety, the result is an increase in real output.[99] Presumably, the firm will have some degree of appropriability over this quality improvement, which should be reflected in higher prices, increased sales, or both.

While a firm may reap a short-term benefit from its IT investment, in a reasonably competitive industry, the innovation will be quickly duplicated in rival firms. IT hardware, software, and expertise are all available in the market, and hence there are no inherent barriers that allow a firm to reap a sustainable advantage from an innovation that is solely IT-based.[100] Once the innovation is standard, competition will drive prices back toward marginal cost and/or restore market share to original levels. The IT system has become a *competitive necessity* in the industry: it is necessary to compete, but provides no advantage over rivals because all have the same system (Clemons, 1991).

Once equilibrium has been restored in the market, measures of firm sales or market share will not be increased. Likewise, if the unpriced quality improvements are not accounted for, the industry appears no better off for its round of IT investment. However, value has been added to the output of all firms, and is accruing to consumers. The real output of the firms and the industry they comprise has increased.

Compounding the output measurement problem is the fact that the majority of IT investment has been in the service sector, or in the "service" functions of non-service firms; the output of these activities are very difficult to measure (Griliches, 1994; Gordon, 1996). The BLS has recently acknowledged this problem, and estimates that its practice of using input-based method to estimate output in certain service industries (e.g., finance, insurance) likely leads to an understatement of productivity growth in about 14 percent of the business sector (Eldridge, 1999).

Of course, estimation of a production function requires measures of inputs as well as of outputs. While measures of "traditional" inputs (capital, labour, materials) are well-understood, the measurement of IT inputs has been more difficult. The electronic computer industry has been characterised by extremely rapid technological innovation over the last 50 years. This technological improvement has resulted in a several-orders-of-magnitude drop in the price performance ratio of processors and memory, and a

---

[99] There is evidence that IT investments are increasingly geared toward these objectives. See the OECD report "Technology, Productivity, and Job Creation," 1996.

[100] While some firms have reaped a long-term benefit from an information system (for example, American Airline's SABRE reservation system), they have done so due to other barriers to entry, such as economies of scale or access to complementary assets.

somewhat slower but still dramatic drop in the price of peripherals such as disk drives and printers.

This unprecedentedly rapid improvement in quality has posed a very challenging measurement problem. This problem has been addressed with hedonic methods, and a number of reasonable price indexes have been constructed for mainframe computers and their peripherals. A joint IBM-BEA project (Cole et al., 1986; Cartwright, 1986) resulted in the adoption of a hedonic index for use in the national accounts. "Exploratory" work on a price index for microcomputers has also been conducted; the most formal to date is (Berndt et al., 1995).

Unfortunately, constructing a price index for computer hardware does not fully resolve the measurement issue. In the case of mainframe computers, individual components (e.g., processors, disk drives, and terminals) are not inherently useful, but must be used as part of an overall system. While the price indexes for computer system components account for the quality improvement in each separate piece, the "quality" of the overall system has not been measured or accounted for in a price index for *computer systems*. There is reason to believe that the improvement of system performance over time may vary from the aggregated rates of improvement of its components (Triplett, 1989). The same argument can be applied to microcomputers, as no price index has yet utilised quality metrics that assess overall system performance.

One alternative to using price indexes and depreciation to convert measures of IT spending into measures of IT capital stock is to attempt to directly measure the market value of a firm's capital stock. In practice, this approach requires an accurate measure of the resale value of each piece of equipment. In comparing two data sets that measure the market value of firm IT assets, Lichtenberg finds a relatively low correlation between the measures for the same firms. This finding leads him to conclude "The data suggest that accurate measurement of the replacement cost of computer assets seems to be much more difficult than measurement of IS budgets and employment...."[101]

Measures of the market value of IT assets incorporate two effects on the value of IT assets: physical depreciation (i.e., machines wearing out), and the asset price declines due to the continuing improvement in the price/performance ratio of new machines. Griliches reflects on this issue in the agricultural sector:

> I turned early to the evidence of used machinery markets to point out that the official depreciation numbers were too high, that they were leading to an underestimate of actual capital accumulation in agriculture, but I also argued that the observed depreciation rates in second-hand markets contain a large obsolescence component that is induced by the rising quality of new machines. This depreciation is a valid subtraction from the present value of a machine in current prices but it is not the right concept to be used in the construction of a constant quality notion of the flow of services from the existing capital stock in "constant prices." The fact that the new machines are better does not imply that the "real" flow of services

[101] Lichtenberg (1995), p. 215.

available from the old machines has declined, either potentially or actually.[102]

Thus, even if reliable measures of market value of IT assets could be obtained, they would not be desirable for use in estimating the IT capital stock for use in production function estimation due to their underestimation of the flow of services available. Therefore, the best option is a measure of real capital stock constructed from (deflated) purchases over time, requiring the application of a computer price index to account for quality change.

Even perfect measures of quality change for computer hardware would not put to rest the issue of measuring IT inputs. Rather, two problems remain. First, computer hardware is not inherently productive, but is a complement to computer software at a number of levels: operating systems (OSs), and application software at a minimum, and perhaps database management systems (DBMSs) and middleware. To accurately measure quality improvement in IT inputs, one must take the approach of measuring user value derived from those inputs.[103] For IT, one must measure the quantity of useful outputs that come from the hardware-software combination, rather than just the raw rate of numerical calculation of which the hardware is capable. This problem has yet to be addressed, either by using benchmark tests on combined hardware-software or by constructing price indexes for software and combining these with the price indexes for hardware.[104] The BLS does not have a software price index, which is troublesome at a time when software is the single largest non-labour expense for some companies.[105]

Likewise, computers are increasingly becoming a complement to communications networks, either internal to a firm on a local area network (LAN) or intranet, or between firms via the Internet or other network. In the 1990s, networking emerged as one of the chief sources of value arising from IT, but no work has been done to measure quality change in network technology or to construct a price index for networking.[106]

The second problem in measuring IT inputs arises from the conversion of IT investment to IT capital stock. Firm spending on IT should be adjusted by the appropriate price index to get a measure of the investment in real terms; however, the conversion of real spending to real capital has not been formally addressed.[107] While used computers suffer a significant drop in their resale value (on the order of 30% per year), they do not, strictly speaking, wear out or become "less useful" over time.[108] However, the

---

[102] Griliches (1990), p. 192

[103] A price index can either focus on user value, which is appropriate for cost-of-living or input-cost indexes, or focus on resource cost, which is appropriate for a producer price index. See Triplett (1989) for a discussion of the user value versus resource cost debate.

[104] There have been some efforts to construct price indexes for software. See the discussion of software price indexes in chapter 2.

[105] Mandel (1994)

[106] Research, sponsored by Cisco Systems, Inc., is currently underway at the University of Texas at Austin to develop a price index for network hardware.

[107] The sole exception being Lehr and Lichtenberg (1997), who use two overlapping data sets to regress spending on capital stock and "backcast" capital stock from the data set with numbers on spending. This approach, while ingenious, is not formally based on underlying theory.

[108] The practice of continuing to run the same systems on the same hardware (or a series of compatible hardware), is known as "legacy systems." This practice is not uncommon, though it has a number of undesirable consequences.

relationship between hardware, software, and user value does change the value of installed hardware over time. Successive generations of software tend to consume increasing computations and memory space, making it difficult to run new software on old hardware. In this sense, old hardware becomes "less useful" as expectations are raised by new software.

A related issue in measuring capital stock is the conversion of "IS labour" to capital stock. Firms have long engaged in custom software and system development, in which labour is transformed to assets, either software or IT infrastructure. The magnitude of such investments certainly warrants attempts at measurement, as firms can have systems for which the lines of code number in the millions and for which the value is estimated in the billions of dollars.[109]

The process of software development is much like research and development (R&D), in that the payoffs are stochastic and hence inherently uncertain. The popular press is rife with stories of large systems development projects that consumed millions of dollars, and ultimately yielded nothing.[110] Of systems development projects, the conventional wisdom is that about 40% are outright failures that never produce a working system, about 60% produce a system that is a moderate success (i.e., it works, but it has fewer features and capabilities than originally planned and fails to achieve all the planned benefits), and a very small proportion of systems are a dramatic success, yielding a competitive advantage and a huge payoff. Interestingly, our competence at software "engineering" has not appeared to improve over time, as measured by the proportion of failures.[111]

To date, only *ad hoc* methods have been applied to this problem. For example, one approach has been to construct a measure of "IS labour-stock" by multiplying yearly IS labour spending by three (Brynjolfsson and Hitt, 1995).[112] More frequently, IS labour is ignored or treated as a direct input to the production process of the firm. A formal method of modelling and measuring the conversion of IS labour to capital stock has yet to be developed. Such a method would need to account for the uncertain nature of systems development, and perhaps a model of R&D can be adapted. This model would also need to incorporate at least two other factors: (i) systems can be developed to meet a number of different objectives, and it would be naive to assume that they should all have the same rate of return; thus, the mixture of projects in the "portfolio" of the firm should be accounted for and measured separately (Applegate et al. 1999); and (ii) firms differ on their degree of competence at systems development, i.e., their ability to successfully translate labour into capital. A direct measure of this "conversion effectiveness" (Weill, 1992) should also be incorporated in the model.

---

[109] Anon. (1995)

[110] The results of a recent (1995) survey by a market research firm on IS failure are available at: http://www.standishgroup.com/chaos.html

[111] One explanation is that software engineering, unlike other forms of engineering, has to deal with a completely dynamic environment that undermines the accretion of knowledge. The argument goes that the hardware, software, and networks that underlie systems change at such a rapid pace that each new project is very much like starting from scratch with only the most rudimentary set of rules of thumb for guidance.

[112] This approach, which, in the absence of theoretical justification, appears arbitrary, was likely a necessary compromise to avoid losing observations in the relatively short data set.

Lags

The core idea behind the lags explanation to the productivity paradox is that there is a time lag between the costs of investment in computers or information technology and the resulting benefits. These lags, the argument goes, have prevented us from measuring the real, productive impact of computers.

There are two primary versions of the lags argument. The first simply asserts that there is a long lag between spending on IT and the benefits it brings. Brynjolfsson remarks, "If managers are rationally accounting for lags, this explanation for low IT productivity growth is particularly optimistic. In the future, not only should we reap the then-current benefits of the technology, but also enough additional benefits to make up for the extra costs we are currently incurring."[113] This proposition would require that managers are willing to tolerate exceptionally long pay-back periods on IT projects. For such projects to have a positive net present value (NPV), either an unusually low discount rate must be applied or the delayed payoffs must be of exceptional magnitude. It is an empirical question whether managers are willing to tolerate lower rates of return on IT projects in the hope that learning curve effects will yield higher payoffs on subsequent projects, but the likelihood of large, delayed payoffs to decades-old IT investments seems slim.

The second lags argument, developed by Paul David, hypothesises that there is a decades-long period of adjustment following the introduction of a new general-purpose technology before it will be used productively. In constructing his argument, he compares the introduction of the electronic computer to the introduction of the electric dynamo:

> Although the analogy between information technology and electrical technology would have many limitations if taken very literally, it proves illuminating nonetheless. Computer and dynamo each form the nodal elements of physically distributed (transmission) networks. Both occupy key positions in a web of strongly complementary technical relationships that give rise to "network externality effects" of various kinds, and so make issues of compatibility and standardisation important for business strategy and public policy.... In both instances, we can recognise the emergence of an extended trajectory of incremental technical improvements, the gradual and protracted process of diffusion into widespread use, and the confluence with other streams of technological innovation, all of which are interdependent features of the dynamic process through which a general purpose engine acquires a broad domain of specific applications.... Moreover, each of the principal empirical phenomena that make up modern perceptions of a productivity paradox had its striking historical precedent in the conditions that obtained a little less than a century ago in the industrialised West, including the pronounced slowdown in industrial and aggregate productivity growth experienced during the 1890-1913 era by the two leading industrial countries, Britain and the United States.... In 1900,

---

[113] Brynjolfsson (1993), p. 75

> contemporary observers well might have remarked that the electric dynamos were to be seen "everywhere but in the productivity statistics!"[114]

The eventual benefits that arise from the new technology are not derived from its direct substitution for the previous technology, but arise from secondary and tertiary effects of adjusting the productive process to take advantage of the capabilities of the new technology. Thus, we should not expect major productivity gains from "automational" uses of IT, for example in replacing filing clerks. The descriptions David provides of adapting productive processes to take advantage of the flexible capabilities of the dynamo have very strong parallels to the stories in the general management literature of "business process reengineering" (BPR).

BPR has been defined in various ways by various authors, but one of the first definitions was:

> Business process reengineering is the fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in critical, contemporary measures of performance, such as cost, quality, service, and speed.[115]

A business process, in turn, is defined as "... a collection of activities that takes one or more kinds of inputs and creates an output that is of value to the customer."[116] This definition of BPR does not explicitly acknowledge a role for information technology, but IT is typically seen as a necessary component of BPR (Davenport, 1993; Brydon et al., 1995); the capabilities of IT are what enable "the fundamental rethinking and radical redesign of business processes."

The close parallel between BPR, with its high failure rate but spectacular successes, and David's "secondary and tertiary adjustments," with its slow pace and anything-but-automatic productivity improvements, provides face validity to this lags explanation to the productivity paradox. By this argument, the productivity effects of computers will gradually improve as the knowledge of the productive application of computers diffuses throughout the economy. Thus, early investment in IT can be viewed in one of two ways. The first treats these investments is a necessary investment in building knowledge about the process of using IT effectively. These early investments will enable future, profitable investments, but will never yield a direct (though delayed) productivity benefit. The second approach takes note of the fact that new general purpose technologies tend to introduce new classes of goods that are not taken account in national productivity statistics (David, 1990). Note that these investments may have been rational in the sense that they produced a positive net return; the fact that an investment did not improve productivity (as measured) does not necessarily render it unprofitable. It has been demonstrated that the investment in the capability to produce new goods has an opportunity cost in that it reduces the economy's ability to produce existing goods. However, the expansion of types of goods available to the consumer results in an increase in welfare, and should be treated, in itself, as an expansion of real output (Diewert and Fox, 1997). Whether the increased choice is inherently valued in

---

[114] David (1990), p. 355-356

[115] Hammer and Champy (1993), p. 32

[116] Hammer and Champy (1993), p. 35

the productivity statistics, the national accounting procedures will eventually begin to measure the productivity improvements of IT as they are revised to include the new goods and services that IT makes possible. Thus, the lags explanation for the productivity paradox can also be viewed as a variation on the mismeasurement explanation.

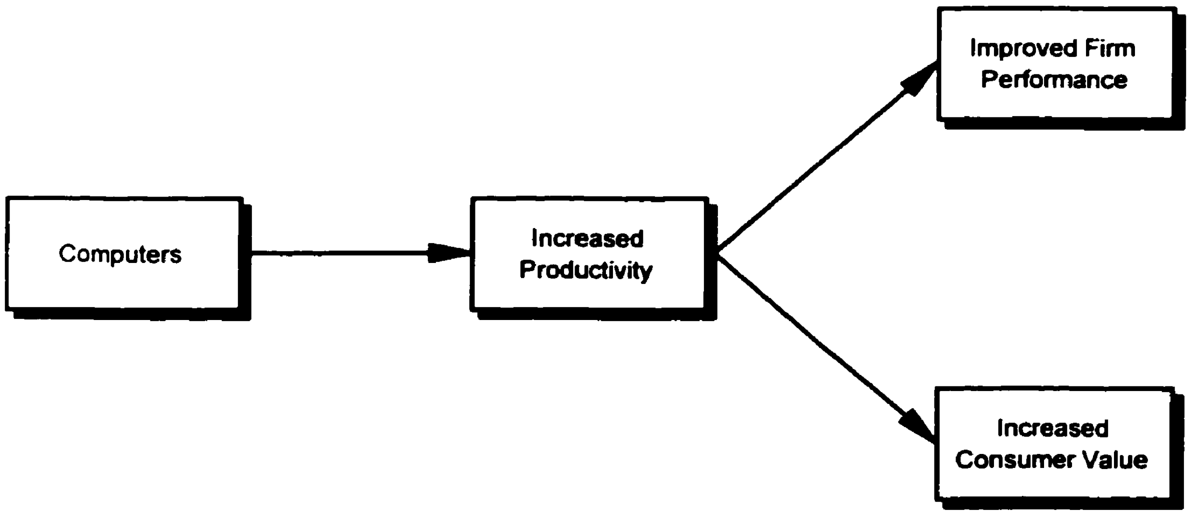
Redistribution

A third explanation for the productivity paradox is that computers do increase productivity, but these gains are not captured by firms but are instead redistributed to consumers (or workers) through competition. Since the productivity gains are either given away or competed away, measurement of nominal firm output will not reveal any productivity improvement. Thus, the redistribution argument is a variation on the mismeasurement theme.

Hitt and Brynjolfsson (1994) differentiates three measures of IT value—productivity, consumer value, and business performance—and argues that they are "separate questions." The authors find that "...computers have led to higher productivity and created substantial value for consumers, but that these benefits have not resulted in measurable improvements in business performance."[117]

This paper takes the position that these the three measures of IT value fall into two categories: efficiency and distribution. Efficiency is the more fundamental category, asking the question "Do computers produce value?" The distribution category addresses the question "Who gets this value, firms or consumers?" The relationship is depicted in **Figure 9**, in which the arrows represent necessary, but not sufficient conditions.

Figure 9: The Primary and Secondary Impact of Computers



The first question can be addressed using the theory of production. Under this approach, a production function is fit to firm-level data on inputs (typically, capital, labour,

[117] Hitt and Brynjolfsson (1994), p. 263

and IT capital have been used) and outputs. Theories of competitive strategy and the theory of the consumer can be used to address the second question. Hitt and Brynjolfsson (1994) makes an important point with regard to computers and firm profits:

> As Porter (1980) has pointed out, in a competitive market with free entry, firms cannot earn supranormal profits because that would encourage other firms to enter and drive down prices. Normal accounting profits will be just enough to pay for the cost of capital and compensate the owners for any unique inputs to productions (e.g., managerial expertise) that they provided. Therefore, an input such as computers, which may be very productive, will not confer supranormal profits to any firm in an industry if it is freely available to all participants in that industry. In equilibrium, all firms will use such an input, but none will gain a competitive advantage from it.[118]

Thus, we should not be surprised that IT fails to return supranormal profits except where barriers to entry exist. Some of the long-cited successful IT projects do rest on barriers to entry. For example, American Airline's SABRE reservation system—which is considered more profitable than the airline—is protected by barriers to entry: a large installed base with travel agents leading to a "lock-in" effect; sufficient bargaining power (due to scale) to require travel agents to have only one reservation system; economies of scope; and the large cost and risk to developing rival systems.[119] Studies, including Hitt and Brynjolfsson (1994), that have directly addressed the effects of IT projects on firm performance (as measured by either profitability or shareholder return) have found little correlation between the two, but have generally suffered from low predictive power (see also Dos Santos, Peffers, and Mauer, 1993).

The direct approach to measuring consumer value arising from quality changes in a class of goods would be to construct an index that combines quality and price change. While the BEA attempts to account for price and quality change from the point of view of the producer with its producer price indexes (PPIs), these suffer from a number of deficiencies when used as an index of consumer value (Triplett, 1989). A more appropriate method is to fit a hedonic function (discussed in Section 3.1 below) to the prices of the goods and the attributes of these goods that provide value to consumers. This technique has been applied to a number of goods, most notably automobiles (e.g., Court, 1956; Griliches, 1961).

The hedonic method requires detailed time series data on the prices of goods and their attributes. These data must be combined with a thorough understanding of the sources of consumer value from the good as well as appropriate specification of functional form for the hedonic function. Even for a good as well-studied as computers, one or more of these requirements fails to be met in the typical study (Triplett, 1989). In order to understand the overall impact of IT on consumer welfare, a hedonic price index would have to be constructed for each class of goods whose quality is thought to be affected by IT—a daunting empirical challenge.

---

[118] Hitt and Brynjolfsson (1994), p. 265

[119] See Applegate et al. (1999)

A second, indirect method exists to attempt to measure the consumer surplus arising from business investment in IT. This approach attempts to estimate consumer welfare by constructing a derived demand curve for computers as an intermediate input. Bresnahan (1986) examined the use of IT in the financial services sector, demonstrating that, under the appropriate conditions, the area under the derived demand curve for computers represents a welfare index. Because computers have undergone a rapid and sustained drop in cost (in terms of price per unit of performance), it is relatively easy to construct a derived demand curve. In looking at the period 1958-1986, he concludes:

> So in current (1986) terms, the downstream benefits of technical progress in mainframe computers since 1958 are conservatively estimated at 1.5 to 2 orders of magnitude larger than expenditures, at least in this high-value use [the financial services sector].[120]

The result that computers have returned benefits (to consumers, not firms) on the order of 30 to 100 times expenditures is startling when juxtaposed with the lack of financial returns for the firms making these IT investments. The method developed by Bresnahan has been reapplied (Hitt and Brynjolfsson, 1994; Lehr and Lichtenberg, 1996; Brynjolfsson, 1996). All of these studies yielded the result that the price decline in computing hardware has resulted in large increases in consumer welfare.

The method of estimating consumer surplus using the derived demand curve has the advantage of not needing measures of firm or industry output. "As Zvi Griliches (1979) points out, important post-war technological advances, such as those in electronics and health, have largely benefited downstream sectors in which the spillovers are hard to measure. The downstream sectors—services, government, health care, etc.—lack sensible measures of real output, so that calculation of the impact of the new technology is difficult."[121] While the Bresnahan method nicely side-steps the issue of real output measurement, this benefit must be weighed against the validity cost of the required assumptions.

In order for the approach of direct estimation of consumer welfare to be valid, two conditions must be met. First, the quality-adjusted price indexes for computers need to be accurate and valid. Second, the industry studied is must be competitive, and thus acting as an agent on behalf of consumers to purchase the "correct" quantity of computers. Given the number of studies and the degree in convergence between the results, it is probably safe to say that the first condition is satisfied for mainframe computer processors (i.e., the price indexes are reliable). However, there has been significantly less work done on price indexes for microcomputers. The second requirement will never be fully met in practice, i.e., there are no *perfectly* competitive industries. The extent to which this assumption is violated in the financial services sector (and the effects of violating this assumption) is unknown. Work subsequent to Bresnahan (1986) has examined a number of industries, thus requiring the assumption that the majority of the economy is operating as if perfect competition were taking place (Hitt and Brynjolfsson, 1994; Brynjolfsson, 1996).

---

[120] Bresnahan (1986), p. 753

[121] Bresnahan (1986), p. 742

The validity of these consumer value estimations has been questioned; for example, Landauer (1995) finds the magnitude of the estimated benefits implausible. While pointing to the results in question is not an effective way to refute a result, the criticism of this method does have some basis. Given the key assumptions of the method, it cannot fail to find a large contribution to consumer welfare.

The several-orders-of-magnitude fall in computer prices (in quality adjusted terms), combined with the increased purchases of computers, traces out the derived demand curve in price and quantity space for computers. This demand curve forms the hypotenuse of a triangle whose other two sides are formed by the quantity = zero line and the price = p^* line, where p^* is the current price of computers. The interior of this triangle represents the consumer surplus gained due to the fall in computer prices. While the "guaranteed" nature of these consumer surplus calculations does not make them invalid, we should not be surprised by the existence or magnitude of the results, provided that we are ready to accept the necessary assumptions.

IT Does Not Improve Productivity

The second major class of explanations for the productivity paradox finds no surprise in the apparent lack of productivity benefits from IT because IT does not, in fact, improve productivity. To accept this argument requires that a monumental violation of the fundamental economic principle of rationality be accepted.

If computers do not improve productivity, then firms (or their agents, managers) have been consistently wrong about their investments in computers: either they have been underestimating the cost of computers, or they have been overestimating the benefit of computers, or both. Not only does this explanation require that managers are behaving irrationally, but it also requires that they have continued to behave irrationally for more than 50 years, at an increasing rate! Because all measures of spending on computers—nominal, inflation-adjusted, and "real" or quality-adjusted—have increased significantly and steadily over the last 50 years, managers must have been making mistakes at an increasing rate, all the while failing to learn from their previous mistakes. Such an argument ignores the tradition of treating expressed preferences as sovereign.

So, why would managers/consumers continue to buy computers if they do not improve productivity? Possible explanations include:

- **organisational inefficiency or mismanagement**—managers have simply been making poor decisions and over-investing in computers (Brynjolfsson, 1993);

- **inherent utility without productivity**—managers have been buying computers because they are fun gadgets, but computers do not improve productivity, perhaps because the applications to which they have been put are poorly designed and not user-friendly (Landauer, 1995; Hamermesh and Oster, 1998);

- **lack of competition**—firms in the service sector have not been exposed to international competition; without this pressure, they have used computers to build organisational slack (Roach, 1991);

- **too rapid pace of change**—the rapid evolution of computer hardware has created adjustment costs (in designing and building new systems and training users to use them) which, unexpectedly for decision-makers, outweigh the benefits;[122]

- **objective**—firms have been using computers to gain market share without improving productivity (Landauer, 1995)

With the exception of the last argument, it is not possible to significantly discredit these explanations. Certainly, with an issue as complicated as the productivity paradox, it is fair to say that each of the above explanations has been present on some occasions in some firms. However, within the communities of information systems (IS) academics and practitioners, the belief that, exceptions aside, IT contributes to productivity is still strongly held. The failure to demonstrate these benefits, and the resultant on-going debate have been a source of embarrassment to both communities.

Paul Strassman argues that the relationship between IT and productivity is not an automatic one:

> Computers are only tools. They are not an unqualified blessing. Identical machines with identical software will perform admirably in one company but will make things worse in an enterprise that has inferior management. They enhance sound business practices. They also aggravate inefficiencies whenever the people who use them are disorganised and unresponsive to customers' needs. The best computer technologies will always add unnecessary costs to a poorly managed firm. The problem seems to rest not with the inherent capabilities of the technologies, which are awesome, but with the managerial inability to use them effectively. ...Business productivity has roots in well organised, well motivated, and knowledgeable people who understand what to do with all of the information that shows up on their computer screens. It would be too much to hope for such excellence to prevail in all businesses. If computer expenditures and corporate profits show no correlation, it is a reflection of the human condition that excellence is an uneven occurrence. It is unrealistic to expect that computerisation could ever change that.[123]

The essence of Strassmann's argument is that computers are "only tools" and that productive use of computers requires good management or "excellence." However, lathes, assembly lines, and robots are also "only tools," but researchers have had no trouble demonstrating the return to these and other forms of non-IT capital. It is unlikely that all the firms using (non-IT) capital for production had the "excellence" of which Strassmann speaks, so it appears that the productive use of capital is well-understood by the average firm. The fact that the productive use of computers is not well-understood by the average firm is a variation on the lags argument—IT will be productive (for everyone) once we all learn how to use it.

This section closes with a refutation of the notion that computers have been used for the "wrong" objective. Some have argued that computers may be put to use for "distributional" goals, rather than productive goals (Landauer, 1995). Big firms, the

---

[122] This viewpoint has been attributed to Alan Blinder.

[123] Strassmann (1997), p. 75

argument goes, spend millions on computers in a sophisticated war for market share that ultimately leaves consumers no better off. However, if one considers the underlying consumer behaviour, this argument loses credibility.

When a consumer switches from brand A to brand B, marketing and economic theory permit three explanations: (i) the value of brand A has decreased; (ii) the value of brand B has increased; or (iii) the consumer is engaging in "variety seeking" behaviour.[124] Consider firm B (which markets brand B) using IT to gain a significant market share from brand A. If we presume that this use of IT can have no effect on the quality of brand A, we can rule out explanation (i) for consumers switching brands. Likewise, while (iii) will cause a number of individuals to switch from A to B, it will also cause some individuals to switch from B to A. In the aggregate, variety seeking will not account for a shift in market share. Thus, only (ii) remains to explain the aggregate shift from A to B: in some way, Firm B has used IT to *add value* to its product from the point of view of consumers. This added value, whether it is in the form of targeted advertising, more customised products, faster service, or better support represents *productive* use of IT. While the ends may be distributional, the means must be productive. The fact that this added value may go unmeasured by traditional techniques does not make it any less real or valuable to the consumer.

There Is No Paradox

The final position is that there is no productivity paradox, at least at the economy level. David Romer makes this case nicely in his comment on the paper by Baily and Gordon that provided the opening quote for this chapter:

> Let me now turn to the "computer puzzle." One of the central questions running through the paper is "What have all those computers been doing?" or, more prosaically, "Why has the vast increase in investment in computer power not been reflected in higher measured productivity growth?" It seems to me that there is no mystery here at all. It is a basic rule of growth accounting that large changes in investment cause only small changes in output. The reasons for this are that investment is a small fraction of GNP and that the marginal product of capital is small. Since computers are a quite small part of total investment, a vast increase in investment in computers would yield only a small increase in measured output even if all the computers were being used productively and were generating measured output.
>
> To be more precise about this, consider the following calculation. Suppose that computers depreciate linearly over eight years and that the marginal product of capital is 15 percent; reasonable variations in these parameters would have little effect on what follows. With these parameters, the stock of real computing capital grew by a factor of 30 from 1965 to 1986. Despite this vast increase, however, the stock of computing capital in 1986 amounted to only about $210 billion in 1982 dollars, or about 6% of a year's GNP. If the marginal product of capital is

[124] Here, consumer value is thought of value net of purchase price, so an innovation that reduces the price of brand A would, by definition, increase its value.

0.15, it follows that computers are increasing output by slightly under 1 percent. These calculations imply that if computers are being used productively, the have raised the average annual growth rate of output over the past two decades by roughly a twenty-fifth of a percentage point. I can imagine sensible variations on this calculation that would raise or lower this figure, either for the economy as a whole or for specific industries, by a few factors of two. But the number seems to be in the right ballpark. In short, asking why the vast investment in computers has not had a discernible impact on productivity growth is like asking why the pull of gravity is not noticeably stronger when the moon is on the opposite side of the earth that when the moon is above us.[125]

Others have made a similar assessment of the very small role of computer equipment as a share of capital stock: it would be unreasonable to expect a large contribution to productivity growth from computers, and it is not surprising that we have not been able to measure their contribution (e.g., Brynjolfsson, 1993; Oliner and Sichel, 1994; Lehr and Lichtenberg, 1997). Oliner and Sichel (1994) quote statistics that computer equipment account for about 2% of property, plant, and equipment (PPE) in the US economy.[126] Rough calculations show that the growth of computers from zero to two percent of PPE over a 50 year period would not have contributed noticeably to output growth or productivity growth. However, the figure representing the share of PPE attributable to IT depends on the definition of IT. If telecommunications infrastructure and software are included in the definition of IT, the share of PPE attributable to IT rises to 12% (Paradox Lost, 1996).

Summary of Candidate Explanations

A remarkable breadth of explanations, ranging from unfriendly software to irrational investment, have been proposed for the productivity paradox. However, one central theme emerges from the more rigorous analyses: measurement problems. To date, assessing the impact of IT investment has been hampered by the relatively crude state of measurement of both IT as an input to production and of the real output of business processes making use of IT. This argument is obviously central to the mismeasurement explanation, but is also prominent in the redistribution and lags positions. According to the redistribution hypothesis, IT investments are producing benefits that are appropriated by consumers through competition or other means. However, these benefits should be measured in any sensible account of real output, and thus the redistribution argument rests on the failure of output measures to account for quality change. Likewise, the lags argument makes note of the tendency of new general purpose technologies to produce new goods and services that are, for a time, not included in the national accounting system. Thus, while IT is improving real output, its contribution is going unmeasured until the accounting system is revised to include these new categories of goods and services.

In conclusion, mismeasurement remains a strong candidate explanation for both the Solow Paradox, and the Productivity Paradox at the economy level (Diewert and Fox,

---

[125] Romer (1988), p. 427-428

[126] Oliner and Sichel (1994), p. 279

1997). This possibility has finally been admitted by the BEA and BLS, which are working on improving their measures of real output and of inflation (Dean, 1999; Eldridge, 1999).

Appendix 2: Survey Instruments

None of the documents presented in this section were developed to be administered on paper; instead, they were designed for a mixture of fax, email, and web browsers. In this section they have been "translated" to a paper-based format as accurately as possible. However, some formatting changes had to be made in order to adapt the material to letter-size pages, so the reader should not presume that the layout was exactly as it was presented to respondents.

Invitation Fax

(next two pages)

THE UNIVERSITY OF BRITISH COLUMBIA
Faculty of Commerce & Business Administration
Management Information Systems Division
2053 Main Mall, Vancouver, BC V6T 1Z2

IT Value Research
Phone: (604) 822-8373
Fax: (604) 822-9574
E-mail: itvr@commerce.ubc.ca
January 19, 1999

Attention: Joe Bloggs

Dear Mr. Bloggs,

The Faculty of Commerce at the University of British Columbia, in collaboration with CIPS and Simon Fraser University, is recruiting experts to participate in a survey related to the business value of information technology. **You have been chosen by the director of CIPS because of your information systems expertise.**

The purpose of this survey is to develop an understanding of the most important sources of business value in IBM-compatible personal computers (PCs). To achieve this goal, we need your input. We believe that your contribution will significantly enhance the results of our study.

Recent surveys of IS managers and CIOs indicate that planning the appropriate corporate IT architecture is a major concern for firms in the 1990s. This planning is complicated by the rapid technological change in computer hardware and networks, as well as the continuing evolution in software and protocols. Unfortunately, it has been difficult to measure the benefits of this technological innovation - just because a PC today is 50 times as fast as a PC ten years ago doesn't mean that it is 50 times as productive or provides 50 times as much business value. The purpose of this survey is to explore the relationship between technological change and business value for an important class of computer hardware - PCs.

We are conducting a three-round survey of forty IS professionals. As a first step, we will send you a **brief questionnaire** asking for your opinion on the most important sources of business value in PC systems. After we receive the completed questionnaires from all participants, we will summarise all of the opinions and send them to you to rank them. This process will be repeated one more time to ensure that consensus is achieved among all participants. We recognise the demands on your time and promise that **your time commitment will be minimal**. Each of the three rounds of the survey will require less than 15 minutes. You will have the option to complete the survey with a series of faxes or via the World Wide Web.

To participate, please complete the enclosed form and fax it to **(604) 822-9574**. In order to participate, we will need to receive your reply by **January 30**. We assure you that your responses will be kept **strictly confidential**. Neither your name nor that of your company will be identified in any of our reports. The results of the survey will be published by CIPS. If you need additional information about this study, please feel free to call Paul Chwelos at 822-8373.

Thank you very much for your time and consideration.

Sincerely yours,

Albert S. Dexter
Professor of MIS

Shayne Gregg
CIPS Director

Paul Chwelos
MIS Ph.D. Candidate

Sponsored by:

Canadian Information Processing Society

Simon Fraser University

The University of British Columbia

IT-VALUE STUDY
Participation Form

Contact Information

(please make corrections, if necessary)

Mr. Joe Bloggs
Senior Partner
Generic IT Consulting
Fax: 555-5555

Title ______________________

Company/Organisation ______________________

Phone Number ______________________

Fax Number ______________________

How would you like to complete the survey?

- ❑ On paper, using faxes
- ❑ Electronically, using email and the World Wide Web

↳ ______________________
Email Address

Background Information

To minimise your time commitment, we will tailor a questionnaire to specifically focus on your point of view. To help us determine which questionnaire to send (or post on the web), please complete the questions below.

1. How many years have you been using PCs? __________
2. How many years have you been managing end-users' use of PCs or client/server? __________
3. How many generations of PCs have you used or managed? (check all that apply)
   - ❑ IMB-PC (XT)
   - ❑ 286 (AT)
   - ❑ 386
   - ❑ 486
   - ❑ Pentium
   - ❑ Pentium-Pro
   - ❑ Pentium-II
   - ❑ Other ______________________
4. Which PC operating systems have you used or managed? (check all that apply)
   - ❑ PC-DOS
   - ❑ MS-DOS
   - ❑ OS/2
   - ❑ MS-Windows 3.x
   - ❑ Windows 95 or 98
   - ❑ Windows NT

User Information

We would also like to survey knowledgeable "power-users" of PCs from business units (i.e., non-IT personnel) to assess their opinions. If you can recommend users to participate in this study, please provide us with their contact information:

Name ______ Title ______ Department ______

Fax Number ______ Email Address ______

Name ______ Title ______ Department ______

Fax Number ______ Email Address ______

PLEASE RETURN THIS PAGE BY FAX TO (604) 822-9574

Round 1 Email

From: IT Value Research <itvr@commerce.ubc.ca>
To: "Joe Bloggs" <chwelos@unixg.ubc.ca>
Subject: IT Value Survey
Message-ID: <19992169004_UBC_ITValue_Research>
Date: Mon, 01 Feb 1999 19:10:04 -0800
X-Mailer: Mabry Internet Control
Status:

Dear Joe Bloggs,

Thank you for agreeing to participate in our survey on the sources of business value in personal computers. Based on the information you provided, we believe that you are an excellent representative of IS managers. Thus, we have placed you in one of two groups of 30 experts who are asked to generate and rank a set of the most important sources of business value in PCs. Because of your particular expertise and the small size of the group, your participation is critical to the successful completion of this study. (Each group will address a different research question, but the results from both groups will be shared with all respondents to the survey.)

The first round of the study is now available on the web. The details of the web site are at the end of this message. Based on our pilot studies, we estimate that it will take you about 15 minutes to complete it. In order to participate in the survey, we will need you to respond by February 6th.

Upon receiving your completed questionnaire, we will integrate and summarise your responses with those from the other experts and then we will send the results back to you for rating. Your responses will be summarised anonymously and be kept strictly confidential. The final results of the study will be published by the sponsoring associations.

If you have any questions regarding this study, please feel free to call me at (604) 822-8373.

Thank you for your time and cooperation.

Web site information:

You will be logged in automatically if you go to:
http://ITValue.commerce.ubc.ca/Welcome.asp?QL=D1R1P140K17203

If you have problems with this, you can go to the home URL for the study:
http://ITValue.commerce.ubc.ca/Welcome.asp

Your username is: "bloggs"
Your initial password is: "Itvalue"
(You may change your password once you log in.)

The University of British Columbia

Faculty of Commerce & Business Administration

IT Value Research Survey

Business Value of PCs Questionnaire

Round 1 Instructions

The purpose of this questionnaire is to draw on your experience with IBM-compatible personal computer (PC) systems to evaluate the most important sources of business value.

For the purposes of this study, a "PC System" includes:

- **The PC itself** (CPU, RAM, hard disk, motherboard, video card, etc., and possibly modem or network cards)
- **Monitor**
- **Standard peripherals** (keyboard, mouse, and possibly speakers)
- **Operating System**

Please note: a "PC System," as defined here, does **not** include **applications software or other peripherals** (e.g., a printer or scanner).

For this round of the survey, we would like you to answer the following question:

> **Imagine that you have been asked for advice on the purchase of PC systems for business use. In your opinion, what are the most important characteristics of PC systems to consider in the purchase decision?**

Note: A **"characteristic"** may apply to an entire PC system, or only to a component of that system. In the context of evaluating photocopiers, for example, a system-level characteristic could be "pages copied per minute" or "warranty," while a component characteristic could be the "size of the paper tray" or the "number of trays in the collator."

You may list as many characteristics as you like, but 5-10 should suffice. If you need to make additional assumptions in order to answer the question, you will be given an opportunity to describe those assumptions at the end of the questionnaire.

Continue...

The University of British Columbia

Faculty of Commerce & Business Administration

IT Value Research Survey

Round 1 Instructions

Please list your opinions below. When listing your suggestions, **provide a one-line description of the characteristic and give a brief explanation of its importance.** An example, again for photocopiers, would be:

Characteristic: **Copy Quality**

Description: In photocopying, it is essential that the reproduction be of very high quality in order to be legible. If the copies are not legible, then the photocopier is nearly useless.

Please provide your opinions on this question:

> **Imagine that you have been asked for advice on the purchase of PC systems for business use. In your opinion, what are the most important characteristics of PC systems to consider in the purchase decision?**

After typing each characteristic, press the "Save and continue" button. When you have finished entering characteristics, press the "Save and exit" button.

To return to the full instructions, click here.

1.

[redacted]

[redacted]

Round 1 Closing

The University of British Columbia

Faculty of Commerce & Business Administration

IT Value Research Survey

Round 1

You have successfully completed Round 1 of the survey. **Thank you very much!** If you reconside the opinions expressed in the questionnaire, or would like to make additions, you will have access to your answers until Friday, February 12th. Simply return to the welcome page and log in, and you suggestions will be available for editing or you may add additional suggestions.

When we have analysed the results and prepared Round 2, we will contact you to participate. Round 2 is scheduled to begin on Monday, February 14th.

If you needed to make additional assumptions in order to answer the question, please describe them in an email.

If you have any questions or concerns about the survey, please contact Paul Chwelos by phone at (604) 822-8373 or drop an email.

University of British Columbia Faculty of Commerce

Round 1 Reminder Email

From: IT Value Research <itvr@commerce.ubc.ca>
To: "Paul Chwelos" <chwelos@unixg.ubc.ca>
Subject: Reminder - IT Value Survey
Message-ID: <19992943556_UBC_ITValue_Research>
Date: Tue, 09 Feb 1999 12:05:56 -0800
X-Mailer: Mabry Internet Control
Status:

Dear Paul Chwelos,

By now, you should have received an email containing the web address for round 1 of the Business Value of IT survey. (The address is also at the bottom of this message.)

This message is a quick reminder that the analysis of round 1 will begin this weekend in order that we may begin round 2 next week. To have your opinions included in the survey, we must receive your completed questionnaire by Saturday, February 13th.

We would like to stress that because of your particular expertise and the small size of the survey group, your participation is critical to the successful completion of this study.

If you have any questions regarding this study, please feel free to call me at (604) 822-8373 or respond to this message.

Again, thank you for your time and cooperation.

Web site information:

You will be logged in automatically if you go to:
http://137.82.154.203/ITValue/Welcome.asp?QL=D4R1P1K7169

If you have problems with this, you can go to the home URL for the study:
http://137.82.154.203/ITValue/Welcome.asp

Your username is: "p"
Your initial password is: "p"
(You may change your password once you log in.)

Round 2 Email

From: IT Value Research <itvr@commerce.ubc.ca>
To: "Joe Bloggs" <chwelos@unixg.ubc.ca>
Subject: IT Value Survey Round 2
Message-ID: <199921555981_UBC_ITValue_Research>
Date: Mon, 15 Feb 1999 15:33:01 -0800
X-Mailer: Mabry Internet Control
Status:

Dear Joe Bloggs,

Thank you completing Round 1 of the IT Value Survey. We appreciate the time and effort you put into your responses. Due to the small size of the survey group, your continued participation is essential to the success of this survey.

We have analysed the results from Round 1 of the survey, and round 2 is now ready for you on the website. In this round, you will rate the importance of each of the characteristics of PC systems identified by the respondents in round 1.

Based on our pilot studies, we estimate that it will take you less than 15 minutes to complete round 2. Please complete questionnaire on or before February 19th.

Again, if you have any questions regarding this study, please feel free to call me at (604) 822-8373 or simply reply to this e-mail.

Thank you for your time and cooperation.

Web site information:

You will be logged in automatically if you go to:
http://137.82.154.203/ITValue/Welcome.asp?QL=D1R2P140K1670

If you have problems with this, you can go to the home URL for the study:
http://137.82.154.203/ITValue/Welcome.asp

Your username is: "bloggs"
Your password is: "Itvalue"
(You may change your password once you log in.)

The University of British Columbia

Faculty of Commerce & Business Administration

IT Value Research Survey

Business Value of PCs Questionnaire

Round 2

Thank you very much for providing us with your assessment of the key characteristics to consider in purchasing PC systems. We very much appreciate the time you invested in your response. Your suggestions have been integrated with those of your peers in a list summarising all of the recommendations.

For the second round of the survey, we ask that you review the list and rate the importance of each characteristic. This process will help us develop a short list of the most important characteristics.

For your information, over 80 percent of the participants responded to the initial questionnaire. This result is very encouraging! Because of your expertise and the small sample size, your continued contribution is critical to the success of our study.

After we receive your ratings, we will calculate the average ratings for the group and then determine the level of consensus among the experts in your group. If it is necessary, we may ask you to reconsider your rating in a third round questionnaire to achieve consensus.

If you have any questions about this questionnaire or the study, please feel free to contact Paul Chwelos via email or at (604) 822-8373. Thank you very much for your help on this research project.

Continue...

The University of British Columbia

Faculty of Commerce & Business Administration

IT Value Research Survey

Round 2 Instructions

Please note: a number of respondents indicated characteristics that are of importance in purchasing portable or laptop systems. However, for the sake of clarity and focus, those suggestions are not included in this round. If you would like to participate in (and receive the results of) a similar survey on laptops, send a quick email indicating your willingness to participate by clicking here.

The following list summarises the characteristics of PC systems suggested in round 1, listed in order of their average ranking. In the first round, there was good agreement on the overall set of attributes to consider in purchasing a PC system. Now we would like to know the relative importance of each of those characteristics.

Please consider the question:

> **Imagine that you have been asked for advice on the purchase of PC systems for business use. In your opinion, what are the most important characteristics of PC systems to consider in the purchase decision?**

You are asked to review and **indicate the degree of importance of each of the characteristics below.**

Please rate each characteristic from 1 to 10 using the following scale:

10 Most Important	The most important characteristic; necessary for all PC systems
9	
8	
7 Very Important	A very important characteristic; contributes strongly to the value of a PC system
6	
5	
4 Slightly Important	A less important characteristic, but still a nice addition to a PC system
3	
2	
1 Unimportant	An irrelevant characteristic; unnecessary in a PC system

Important Notes:

1. **You cannot leave this page until you have rated all items.**
2. **Depending on the speed of your Internet connection, the rest of the page may take a few seconds to load.**
3. **If you would like to make additional comments or suggestions for revising the description of a characteristic, you will be given opportunity to do so on the next page by email.**

1. Performance

The performance of a PC system is a key attribute as users don't want to wait for the machine to calculate results, retrieve data, or open application software. Performance is an emergent characteristic of the a number of components: CPU (generation, Level 1 cache, and clock speed), motherboard architecture (PCI versus ISA) and bus speed, quantity and type of Level 2 cache and RAM, type of drive interface (EIDE versus SCSI). Ideally, these components are purchased in an optimised configuration that eliminates any bottlenecks.

2. RAM

While the quantity and type of RAM contributes to system performance, the quantity of RAM is also important in its own right as more RAM enables multitasking between multiple applications. Likewise, some software is very demanding of RAM and needs a large quantity in order to be installed or operate at an acceptable level of performance. Insufficient RAM is a common bottleneck to system performance.

3. Vendor

The vendor is a critical determinant of a number of characteristics of PC systems. The overall quality, reliability, and expected maintenance cost of systems are largely determined by the vendor's reliability rating. The overall stability of systems (the ability to run without "crashing") is partly determined by the vendor's level of certification of compatibility with hardware (e.g., network and video cards) and software (e.g., operating systems and network software). Likewise, certification for standards that allow for remote management of hardware over a network, such as DMI (Desktop Management Interface), are largely vendor-specific. Finally, choosing a reputable vendor that will exist in the future allows for planning an organisational IT architecture (discussed below) that includes a smaller number of vendors, thus reducing complexity and support costs.

4. Warranty and Service

The type and length of warranty are important because system downtime can be costly and inconvenient. On-site support is preferred, with local service being next-best. Having to ship systems to the manufacturer can be costly and time-consuming. In addition, technical support (over the telephone or Internet) that is oriented toward end-users is valuable.

5. Secondary Storage

The quantity of hard drive space determines the amount of software that can be installed as well as the quantity of data that can be stored locally. Since software continues to expand its use of this resource, it is important to "overbuy" for the future (i.e., buy a hard drive that is larger than needed to meet today's needs).

6. Price

PC system prices fluctuate due to promotions, discontinuations, etc., so it may be possible to get equivalent systems at different prices. However, lower prices generally come with a trade-off of lower quality components or a less reputable vendor (and hence a less stable and reliable system).

7. Display Quality

The clarity of the monitor is an important concern in reducing eyestrain of users and making the overall system more ergonomic. Display quality is a function of the quality of both the monitor (dot pitch and refresh rate) and of the video card (which can also affect refresh rate).

8. Ability to Upgrade

Because component prices continue to fall, it is important to purchase systems that can be upgraded in the future to extend their useful life. Thus, the motherboard should: have room to add additional RAM (without having to remove existing RAM); be able to handle the fastest processor available; and have free slots for adding additional hardware. Likewise the case should have free drive bays for adding additional hard drives; a tower case is probably best. Because the fastest processor on the market tends not to be priced competitively compared to the second or third-fastest clock speed, there exists a "sweet spot" just behind the technology curve that yields a better price/performance ratio. (For example, a 500 MHz Pentium-II CPU is currently more than twice as expensive as a 400 MHz P-II CPU.) Buying a system that can be upgraded in the future allows for exploitation of the sweet spot.

9. Compatibility with IT Architecture

It is important that PC systems be compatible with existing and planned systems and hardware in the organisation. Because network connectivity (see below) is important, PCs need to be able work with existing networks, hardware, and client/server applications. Again, to minimise support costs, it may be of interest to limit the number of PC configurations in the organisation; having many systems with the same video card, network card, etc., allows for a single PC image to be used.

10. Industry Standard Components

Value can be derived from specifying high-quality, industry standard components such as network and video cards. If a standard component is chosen, it is more likely that drivers and technical support information will be available and supported in the future. In addition, if a problem arises (such as an incompatibility between a video card and an industry standard application package), it is likely that many others will have the same problem, and a solution will be available either from the hardware or software providers, or from discussion groups.

11. Operating System

The operating system is the primary determinant of the user interface of the PC, and thus affects the "user friendliness" or ease-of-use of systems. In addition, there is value to using the industry standard OS for availability of application software and compatibility with other systems in the organisation. In addition, the OS to a large extent determines the "stability" of PC systems, that is, their ability to run without crashing or freezing up.

12. Monitor Size

A larger monitor can allow for larger text and less eye strain, or for higher resolutions and more "screen real-estate" for using multiple windows simultaneously. A large desktop prevents users from having to spend their time scrolling up-and-down and side-to-side.

13. Network Connectivity

The PC should have a network card and/or a modem for connecting to the LAN, WAN, or Internet. Network connectivity is necessary to support email, client/server applications, and sharing data across networks. In addition, some users may use the a modem to support telecommuting.

14. External Drives

Drives with removable media, such as CD-ROM and floppy drives are important for installing software.

15. Configured for Lifetime Use

A PC system should be configured with the latest components and processor to meet all anticipated demands during its lifetime. It is expensive to visit and modify a system, so this practice should be avoided where possible.

16. High-Quality Input Devices

The keyboard and the mouse are the primary ways in which users interact with a system, and high-quality "ergonomic" devices are healthier and more pleasant for users. For example, the mouse should be smooth to move and sensitive to small hand motions so users don't waste time and physical energy. In addition, brand-name devices also tend to be more durable.

17. Multimedia Support

The availability of speakers, microphone, video hardware, and perhaps a DVD allow full multimedia support for editing sound, graphics, and video. Multimedia support is important for presentations and training applications.

18. Backup Devices

Drives using either tape or disk-based media (e.g., ZIP, JAZ) allow users to backup their data.

Round 2 Closing

The University of British Columbia

Faculty of Commerce & Business Administration

IT Value Research Survey

Round 2

You have successfully completed Round 2 of the survey. **Thank you very much!** If you hav any comments or suggestions for revision of the descriptions, please click here to send an email message.

As with last round, if you reconsider your ratings, you may return and change them. You will have access to your answers until Sunday, February 21st.

Round 3 is scheduled to begin on Tuesday, February 23rd. We will be in contact with yo Round 3 is ready for completion.

If you have any comments on the survey, please contact Paul Chwelos via email or by phone a (604) 822-8373

University of British Columbia Faculty of Commerce

Round 2 Reminder Email

```
From: IT Value Research <itvr@commerce.ubc.ca>
To: "Paul Shoelace" <chwelos@unixg.ubc.ca>
Subject: Reminder - IT Value Survey Round 2
Message-ID: <199921930460_UBC_ITValue_Research>
Date: Fri, 19 Feb 1999 08:27:40 -0800
X-Mailer: Mabry Internet Control
Status:

Dear Paul Shoelace,

This message is a quick reminder that we need to receive your ranking of the
key characteristics in PC systems by Monday, February 22nd in order to include
them in our analysis.

We would like to stress that because of your particular expertise and the
small size of the survey group, your participation is critical to the
successful completion of this study.

If you have any questions regarding this study, please feel free to call me at
(604) 822-8373 or respond to this message.

Again, thank you for your time and assistance.

Web site information:

You will be logged in automatically if you go to:
http://137.82.154.203/ITValue/Welcome.asp?QL=D1R2P268K14769

If you have problems with this, you can go to the home URL for the study:
http://137.82.154.203/ITValue/Welcome.asp

Your username is: "p1"
Your initial password is: "p1"
(You may change your password once you log in.)
```

Round 3 Email

From: IT Value Research <itvr@commerce.ubc.ca>
To: "Paul Shoelace" <chwelos@unixg.ubc.ca>
Subject: IT Value Survey Round 3
Message-ID: <199922349322_UBC_ITValue_Research>
Date: Tue, 23 Feb 1999 13:42:01 -0800
X-Mailer: Mabry Internet Control
Status:

Dear Paul Shoelace,

First, let me thank you for your continued participation in this survey. Because this survey is based on the opinion of a small group of experts, we need your continued participation to complete this research.

We have analysed the results from Round 2 of the survey, and have compiled an initial ranked list of the key characteristics of PC systems. At this point, we need you to complete round 3, which, like round 2, should be very quick to complete.

Could we ask you to please complete questionnaire on or before February 27th?

As always, if you have any questions regarding this study, please email or call (822-8373).

Thank you for your time and cooperation.

Web site information:

You will be logged in automatically if you go to:
http://137.82.154.203/ITValue/Welcome.asp?QL=D1R3P268K1045

If you have problems with this, you can go to the home URL for the study:
http://137.82.154.203/ITValue/Welcome.asp

Your username is: "p1"
Your password is: "p1"
(You may change your password once you log in.)

The University of British Columbia

Faculty of Commerce & Business Administration

IT Value Research Survey

Business Value of PCs Questionnaire

Round 3

Based on the Round 2 ratings from you and your peers, we have developed an initial ranked list of the most important characteristics of PC systems.

A crucial goal of this research is to achieve a high level of consensus about the importance of each characteristic. To achieve this goal we need your assistance one more time. Your help will enable us to complete the study and develop the final list of key PC system characteristics. Because of the small sample size, your timely input is critical to the success of our study.

We hope you have found your participation in this project to be a meaningful experience. We appreciate the time and effort you invested in your responses. As a token of our appreciation, a copy of the final results will be made available to you.

Thank you very much for your help with this research project.

Continue...

The University of British Columbia

Faculty of Commerce & Business Administration

IT Value Research Survey

Round 3 Instructions

The following list of characteristics of PC systems is presented in order of importance based on the second round ratings. Recall that your decisions should be based on the question below:

> **Imagine that you have been asked for advice on the purchase of PC systems for business use. In your opinion, what are the most important characteristics of PC systems to consider in the purchase decision?**

INSTRUCTIONS: **Our goal in this round is to achieve higher levels of agreement among all participants.** Please review each characteristic, the group's average and your initial rating, and make a new rating decision. If your new rating is different from the group's average by more than three points (or you would like to comment on a recommendation), please explain your decision for your rating in an email at the end of the survey.

Please use the following scale to indicate importance of each characteristic:

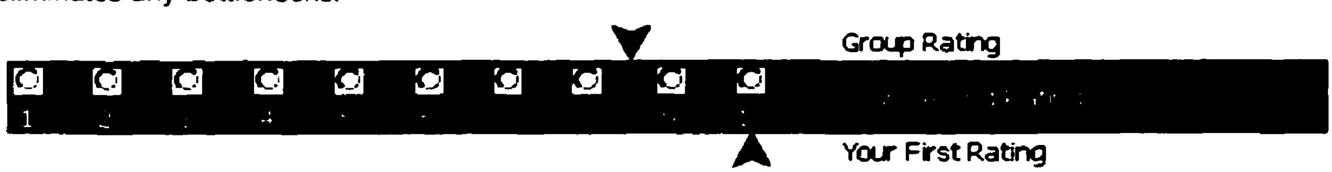
10 Most Important	The most important characteristic; necessary for all PC systems
9	
8	
7 Very Important	A very important characteristic; contributes strongly to the value of a PC system
6	
5	
4 Slightly Important	A less important characteristic, but still a nice addition to a PC system
3	
2	
1 Unimportant	An irrelevant characteristic; unnecessary in a PC system

Important Notes:

4. **You cannot leave this page until you have rated all items.**
5. **Depending on the speed of your Internet connection, the rest of the page may take a few seconds to load.**
6. **If you would like to make additional comments or suggestions for revising the description of a characteristic, you will be given opportunity to do so on the next page by email.**

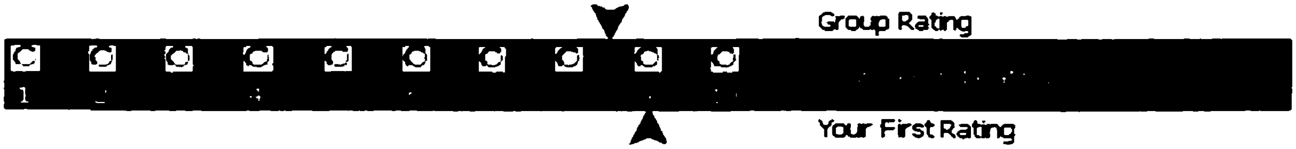
1. Performance

The performance of a PC system is a key attribute as users don't want to wait for the machine to calculate results, retrieve data, or open application software. Performance is an emergent characteristic of the a number of components: CPU (generation, Level 1 cache, and clock speed), motherboard architecture (PCI versus ISA) and bus speed, quantity and type of Level 2 cache and RAM, type of drive interface (EIDE versus SCSI). Ideally, these components are purchased in an optimised configuration that eliminates any bottlenecks.



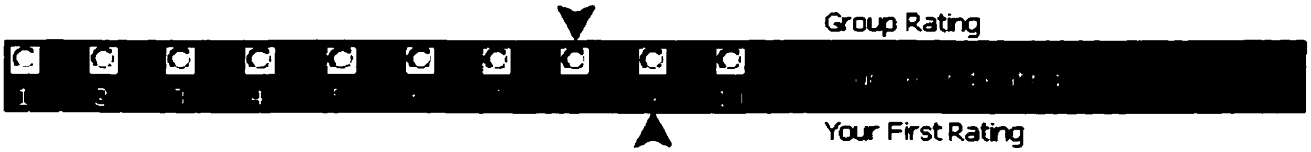
2. Compatibility with IT Architecture

It is important that PC systems be compatible with existing and planned systems and hardware in the organisation. Because network connectivity (see below) is important, PCs need to be able work with existing networks, hardware, and client/server applications. Again, to minimise support costs, it may be of interest to limit the number of PC configurations in the organisation; having many systems with the same video card, network card, etc., allows for a single PC image to be used.



3. Network Connectivity

The PC should have a network card and/or a modem for connecting to the LAN, WAN, or Internet. Network connectivity is necessary to support email, client/server applications, and sharing data across networks. In addition, some users may use the a modem to support telecommuting.



4. RAM

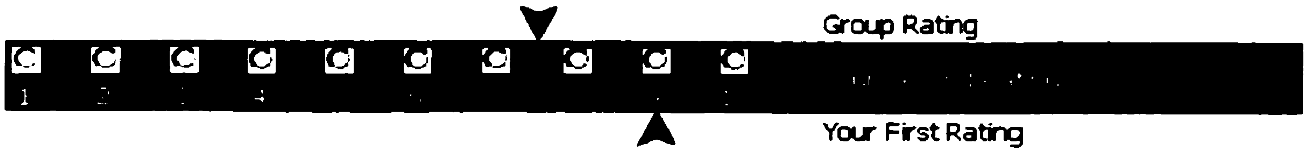
While the quantity and type of RAM contributes to system performance, the quantity of RAM is also important in its own right as more RAM enables multitasking between multiple applications. Likewise, some software is very demanding of RAM and needs a large quantity in order to be installed or operate at an acceptable level of performance. Insufficient RAM is a common bottleneck to system performance.

5. Operating System

The operating system is the primary determinant of the user interface of the PC, and thus affects the "user friendliness" or ease-of-use of systems. In addition, there is value to using the industry standard OS for availability of application software and compatibility with other systems in the organisation. In addition, the OS to a large extent determines the "stability" of PC systems, that is, their ability to run without crashing or freezing up.

6. Industry Standard Components

Value can be derived from specifying high-quality, industry standard components such as network and video cards. If a standard component is chosen, it is more likely that drivers and technical support information will be available and supported in the future. In addition, if a problem arises (such as an incompatibility between a video card and an industry standard application package), it is likely that many others will have the same problem, and a solution will be available either from the hardware or software providers, or from discussion groups.



7. Vendor

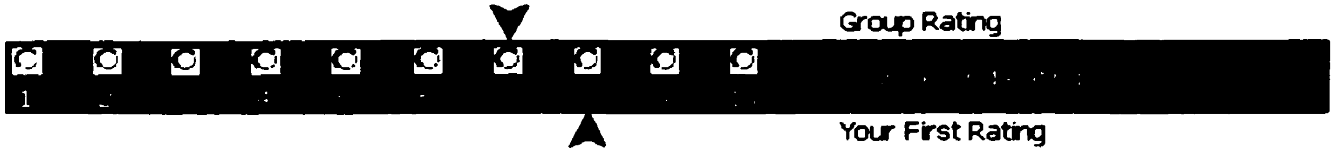
The vendor is a critical determinant of a number of characteristics of PC systems. The overall quality, reliability, and expected maintenance cost of systems are largely determined by the vendor's reliability rating. The overall stability of systems (the ability to run without "crashing") is partly determined by the vendor's level of certification of compatibility with hardware (e.g., network and video cards) and software (e.g., operating systems and network software). Likewise, certification for standards that allow for remote management of hardware over a network, such as DMI (Desktop Management Interface), are largely vendor-specific. Finally, choosing a reputable vendor that will exist in the future allows for planning an organisational IT architecture (discussed below) that includes a smaller number of vendors, thus reducing complexity and support costs.

8. Ability to Upgrade

Because component prices continue to fall, it is important to purchase systems that can be upgraded in the future to extend their useful life. Thus, the motherboard should: have room to add additional RAM (without having to remove existing RAM); be able to handle the fastest processor available; and have free slots for adding additional hardware. Likewise the case should have free drive bays for adding additional hard drives; a tower case is probably best. Because the fastest processor on the market tends not to be priced competitively compared to the second or third-fastest clock speed, there exists a "sweet spot" just behind the technology curve that yields a better price/performance ratio. (For example, a 500 MHz Pentium-II CPU is currently more than twice as expensive as a 400 MHz P-II CPU.) Buying a system that can be upgraded in the future allows for exploitation of the sweet spot.

9. Warranty and Service

The type and length of warranty are important because system downtime can be costly and inconvenient. On-site support is preferred, with local service being next-best. Having to ship systems to the manufacturer can be costly and time-consuming. In addition, technical support (over the telephone or Internet) that is oriented toward end-users is valuable.



10. Secondary Storage

The quantity of hard drive space determines the amount of software that can be installed as well as the quantity of data that can be stored locally. Since software continues to expand its use of this resource, it is important to "overbuy" for the future (i.e., buy a hard drive that is larger than needed to meet today's needs).

11. Display Quality

The clarity of the monitor is an important concern in reducing eyestrain of users and making the overall system more ergonomic. Display quality is a function of the quality of both the monitor (dot pitch and refresh rate) and of the video card (which can also affect refresh rate).

12. External Drives

Drives with removable media, such as CD-ROM and floppy drives are important for installing software.

13. Price

PC system prices fluctuate due to promotions, discontinuations, etc., so it may be possible to get equivalent systems at different prices. However, lower prices generally come with a trade-off of lower quality components or a less reputable vendor (and hence a less stable and reliable system).

14. Monitor Size

A larger monitor can allow for larger text and less eye strain, or for higher resolutions and more "screen real-estate" for using multiple windows simultaneously. A large desktop prevents users from having to spend their time scrolling up-and-down and side-to-side.

15. Backup Devices

Drives using either tape or disk-based media (e.g., ZIP, JAZ) allow users to backup their data.

16. High-Quality Input Devices

The keyboard and the mouse are the primary ways in which users interact with a system, and high-quality "ergonomic" devices are healthier and more pleasant for users. For example, the mouse should be smooth to move and sensitive to small hand motions so users don't waste time and physical energy. In addition, brand-name devices also tend to be more durable.

17. Configured for Lifetime Use

A PC system should be configured with the latest components and processor to meet all anticipated demands during its lifetime. It is expensive to visit and modify a system, so this practice should be avoided where possible.

18. Multimedia Support

The availability of speakers, microphone, video hardware, and perhaps a DVD allow full multimedia support for editing sound, graphics, and video. Multimedia support is important for presentations and training applications.

The University of British Columbia

Faculty of Commerce & Business Administration

IT Value Research Survey

Round 3

If any of your ratings differed from the group average by three points or more, please describe your rationale for these ratings in an email.

You have successfully completed Round 3 of the survey. **Thank you very much for your tim and effort.** As with previous rounds, you have the ability to return and change your ratings i you so desire. You will have access to your ratings until Friday, February 26th.

Once we receive all of the responses, we will analyse them and compile the final results. If sufficient degree of consensus has not been reached, we will ask you to complete round 4. I consensus has been achieved, we will send you the results as soon as they are available.

If you have any comments on the survey, please contact Paul Chwelos via email or by phone a (604) 822-8373

University of British Columbia Faculty of Commerce

Round 3 Reminder Email

From: IT Value Research <itvr@commerce.ubc.ca>
To: "Paul Shoelace" <chwelos@unixg.ubc.ca>
Subject: Reminder - IT Value Survey Round 3
Message-ID: <199922657902_UBC_ITValue_Research>
Date: Fri, 26 Feb 1999 16:05:01 -0800
X-Mailer: Mabry Internet Control
Status:

Dear Paul Shoelace,

This message is a quick reminder that the survey will close next week in order that we may conduct an analysis of the degree of agreement on the ratings of PC characteristics. To have your final rankings included in the survey, we must receive your ratings by March 2nd.

As you know, this research relies on a small number of experts, so we would very much appreciate your continued participation. Pilot tests indicate that round 3 typically takes significantly less time to complete than either rounds 1 or 2.

As a token of our appreciation for your efforts, the results of this study will be made available to all participants.

As always, please call (822-8373) or email if you have any questions.

Again, thank you for your time and cooperation.

Web site information:

You will be logged in automatically if you go to:
http://137.82.154.203/ITValue/Welcome.asp?QL=D1R3P268K1045

If you have problems with this, you can go to the home URL for the study:
http://137.82.154.203/ITValue/Welcome.asp

Your username is: "p1"
Your initial password is: "p1"
(You may change your password once you log in.)