PRICE AND QUALITY OF DESKTOP AND MOBILE PERSONAL COMPUTERS: A QUARTER CENTURY OF HISTORY

by

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ABSTRACT

In this paper we examine quality-adjusted price indexes for personal computers (PCs) from 1976, the year in which PCs were first introduced, through 1999, using hedonic price regression methods. We focus in particular on the equality of coefficients across mobile (luggable, laptop, and notebook) and desktop PCs, and on the stability of coefficients over time.

Using 1976-1999 annual PC data on prices and characteristics, we find quality-adjusted PC prices have fallen by about a factor of about 1600 for desktop models, implying an AAGR of about -27%. Until about 1994, quality-adjusted prices of mobile models did not fall as rapidly as those of desktop PCs, but since then trends have been similar. Price declines have been larger in the 1990s than in the 1970s and 1980s, and have been larger in the late 1990s than in the early part of the decade.

Beginning about 1987 and continuing thereafter, the relationship between prices and PC characteristics differs between desktop and mobile models. Moreover, for desktop models, coefficient estimates on characteristics differ significantly by year beginning in 1987, and for mobile PCs, by 1993. There does not appear to be a monotonic trend in coefficient estimates on characteristics over time.

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I. INTRODUCTION

The year 1976 marked not only the 200th birthday of the United States, but it was also the year in which personal computers were first introduced commercially into the US market. In the quarter century since then, there has been enormous technological progress and quality improvement.[1] For example, IBM-compatible desktop PCs were launched in the early 1980s; luggable, then portable, laptop and eventually notebook PCs came on the scene in the late 1980s and early 1990s. By the late 1990s PCs had evolved with multimedia capabilities, connectivity to the Internet, all in ever smaller physical sizes, and for prices sometimes less than $1000. Today's PCs typically embody megabytes of random access memory, gigabtyes of hard disk memory, and process commands at speeds up to 1000 megahertz. In 1976, PCs had only several kilobytes of RAM, had no hard disk at all, processed commands at snail-like speeds of less than one MHZ, yet cost several thousand dollars.[2]

For government economic statistical agencies publishing measures of price change and real output growth, the tasks of reliably tracking the computer industry and its suppliers, and adjusting prices for quality changes, are formidable ones. Until 1986, the Bureau of Economic Analysis computed real output growth in the computer industry assuming that the implicit price deflator for mainframe computers was constant at 1.000. Following on a collaborative research project with researchers at the IBM Corporation, in 1986 the BEA began adjusting mainframe computer prices for quality change, using hedonic pricing methods.[3] Four years later in 1990, the Bureau of Labor Statistics published its first experimental quality-adjusted producer price index for the mainframe computer industry, also based on hedonic price methods.[4] Today the BLS publishes separate producer price indexes for computers and for semiconductors that incorporate estimates of quality change, and although the BLS' consumer price index does not publish a separate price index for computers, PCs are a component of its CPI item category entitled "Information Processing Equipment".[5]

The hedonic regression methods employed by researchers and government statisticians to adjust PC prices for quality change typically rely on pooled cross-section and time series data, and necessarily assume a certain amount of parameter equality across various models, as well as parameter stability over time. When technological progress is extremely rapid, however, the assumption of parameter stability over time on, say, PC characteristics such as megahertz (MHZ) speed, random access memory (RAM) size and hard disk storage capacity may plausibly be called into question. Similarly, one might expect that the price effects of changes in characteristics over time, such as those involving hard disk memory capacity, might differ for desktop and notebook PCs.

In this paper we report on results from an initial examination of the stability of PC hedonic price coefficients over the past quarter century, and on the equality of the hedonic price coefficients between desktop and mobile models. Using 1976-1999 annual PC data on prices and characteristics, and building on a hedonic aggregation method that apparently was first discussed by Triplett [1990b], we find that beginning in 1987 the relationship between prices and PC characteristics differed between desktops and mobiles, suggesting that based on the Triplett criteria, since 1987 they could not be reliably aggregated. Moreover, by 1987 parameter estimates on desktop PC characteristics differed significantly from each other in adjacent year regressions, implying that parameter estimates varied annually; for mobile PCs, annual variation was significant beginning in 1993. Thus the issues of parameter equality across models, and stability over time, are apparently empirically significant. We discuss implications of parameter instability for price index construction, and consider alternative ways of incorporating the hedonic price measures into price indexes for desktop and mobile PCs. We begin with an overview of data sources and trends.

II. PC DATA SOURCES AND DATA TRENDS

Our 1976-1999 data set covers a remarkable period of technological changes in the PC industry and encompasses revolutionary changes in how individuals use PCs. Our basic unit of observation is a distinctly identified personal computer model available in the US. Over the 24 years, we have 9042 observations, an average of about 375 models per year. Although undoubtedly an incomplete data set, we are reasonably confident that it is representative of trends in the overall market. Most of the data covers machines produced by the larger manufacturers, implying that the models in our data set constitute a large percentage of overall PC market sales.

Our data gathering project has consisted of three separate efforts over the last decade. For the 1976-88 time period, our data come primarily from mail order magazine and newspaper advertisements listing a vendor, model, and computer attributes such as speed, memory, and storage capacity.[6] Although these data sources provided useful information on actual transactions (not just list) prices, the amount of technical information available was limited. Over the 1982-88 time period, proprietary sales data from the International Data Corporation was available for about 950 of the 1,265 models in the estimation sample. The 1976-81 and 1982-88 data are described in greater detail in Berndt and Griliches [1993].

From 1989 through 1999, we rely on a more standardized source of information, namely, Datapro and the Gartner Group. Details on the 1989-92 data are given in Berndt, Griliches and Rappaport [1995]. Briefly, the 1989-92 data come from the Data Information Services Group, then a division of McGraw-Hill. The price data are list prices of the particular base model, rather than transactions prices. However, a considerable amount of data on technical characteristics is available. For a subset of the models, we have proprietary quantity sales data available from the International Data Corporation.[7] From 1993 through 1999, we employ data from the Gartner Group. These data are comparable with the 1989-92 Datapro series. We have not yet been able to gain access to 1993-99 proprietary sales data at the level of individual models, although we are currently investigating the feasibility of employing sales data at the model-processor type level of aggregation.

Although the coverage spans the entire 24 year history of PCs, our data set has a number of limitations. First, the 1982-88 observations capture transactions rather than list prices, while 1989 onward represent list prices. The rapid growth of mail order in the 1990s suggests that the gap between list and transactions prices has likely closed. To the extent this has occurred, it is likely that our price series will overstate price declines since 1989. However, it is widely known that in 1992 major brand manufacturers changed pricing strategies to bring list prices down considerably to match others' transactions prices. Thus, while price declines might be overstated for 1989-92, since then any bias is likely to be much smaller. Moreover, since the principal switch from transactions to list prices occurs between 1988 and 1989, it is likely that we understate any price decline occurring between 1988 and 1989.

A second limitation of our data is that for 1976-81 and since 1993, we do not have access to quantity sales data. Thus in the price index computations we report here, we implicitly weight all models equally. To the extent the demand curve for PCs is downward sloping, we expect that competitive forces would favor PCs with lower quality-adjusted prices, and that leading-selling models would be those experiencing the largest quality-adjusted price declines compared to the previous year's models. To the extent this has occurred, one might expect use of unweighted model data to result in understated price declines. It is worth noting, however, that in Berndt, Griliches and Rappaport [1995], price indexes based on unweighted adjacent year regressions yielded almost identical 1982-88 average annual growth rates (AAGRs) as those based on Divisia indexes employing quantity sales data: the AAGRs were -23.22% and -23.90%, respectively, for mobile PCs, and -31.15% and -31.93% for desktop PCs.

Finally, implementation of hedonic regression methods requires making a decision on what types of variables one should include as regressors to measure the most salient price-determining characteristics. This is particularly problematic when one covers a time period encompassing dramatic technological change, as has occurred in the PC market. To facilitate comparability over time, in this paper we select a limited number of characteristics, but as discussed in the next section, we allow parameter estimates on these characteristics to vary annually, thereby permitting a relatively unrestricted impact of the estimated changes in characteristics on price. The characteristics we focus on here include hard disk memory (in megabytes -- MB), processor speed (in megahertz -- MHZ), the amount of RAM memory (MB), and dummy variables for whether the model included a CD-ROM. To accommodate possible brand effects in a parsimonious manner, we include a dummy variable for computers made by Apple, and another combining many of the "name-brand" IBM-compatible computers (Compaq, Dell, Gateway, HP, IBM, NEC, Toshiba and Zenith). All other brands are therefore in the referenced intercept term.

There are many ways in which one could describe price and quality change in the PC market. Sample means, by year, for prices and a number of characteristics, separately for mobile and desktop models, are given in Appendix Table 1. In Figure 1 we also present a very simple description. On the left vertical axis we plot mean PC model price for each year, on the right vertical axis we plot the mean value of the logarithm of MHZ speed. While mean prices rose from 1976 to about 1989 and then fell again after 1989, over the entire 1976-99 time period there has been a steady increase in mean lnMHZ -- a linear regression of mean lnMHZ on time has a slope coefficient estimate of 0.2362 (R^2 of 0.9558), implying an AAGR of about 27% per year.[8]

III. ISSUES IN SPECIFYING AND ESTIMATING PC HEDONIC PRICE EQUATIONS

We now briefly discussion various specification and estimation issues. Let the price of PC model i in year t be P_{it}, let the value of the j^{th} characteristic for that model be X_{ijt}, and let T_t be a time dummy variable having the value of unity in year t, else being zero.

A. PARAMETER EQUALITY ACROSS DESKTOP AND MOBILE PC MODELS

To examine parameter equality across classes of models, we distinguish desktop PCs from mobile PCs, designating desktops with the first subscript being D, and for mobile PCs, M, i.e., the value of the j^{th} characteristic for desktop (mobile) model i in year t is X_{Dijt} (X_{Mijt}).

In an unrestricted single cross-section specification, separate hedonic regression equations are specified for desktop and mobile PCs:

$$\ln P_{Dijt} = \alpha_{Dt} + Ó_j â_{Djt} X_{Dijt} + \varepsilon_{Dijt} \text{ for desktop PCs, and} \tag{1}$$

$$\ln P_{Mijt} = á_{Mt} + Ó_j ß_{Mjt} X_{Mijt} + \varepsilon_{Mijt} \text{ for mobile PCs,} \tag{2}$$

where ln denotes natural logarithm, the ε's are random disturbance terms, and the á's and â's are parameters to be estimated. Note that $â_{Djt}$ ($â_{Mjt}$) represents the marginal price effect of a small change in desktop (mobile) characteristic j in time period t, other things equal. We employ the log-log hedonic price equation functional form, since based on Box-Cox criteria, in previous research Berndt, Griliches and Rappaport have found it to be the preferred functional form. Hence, when j is a continuous variable, $â_{Djt}$ and $â_{Mjt}$ are partial elasticities of price with respect to characteristic j.

In a partially restricted cross-section specification, all "slope" coefficients are equal across desktop and mobile PCs, but the intercept term is allowed to differ between desktop and mobile PCs, i.e., while $á_{Dt} \neq á_{Mt}$, it is assumed that $â_{Djt} = â_{Mjt} = â_{jt}$ for all j=1,...,J characteristics. Here the marginal effects of a change in each characteristic are the same for desktop and mobile PCs. In this partially restricted yearly specification, the hedonic price equation to be estimated takes the form

$$\ln P_{ijt} = á_{Dt} D_{it} + á_{Mt} M_{it} + Ó_j â_{jt} X_{ijt} + å_{ijt} \tag{3}$$

where P_{ijt} and X_{ijt} are "stacked" vectors of desktop and mobile PC observations, $å_{ijt}$ is a stacked vector of random disturbances for desktop and mobile PCs, D_{it} is a dummy variable equal to one only if model i is a desktop model, else it is zero, and M_{it} is a dummy variable equal to one only if model i is a mobile model, else it is zero.

In a fully restricted cross-section specification, in addition to the constraint that laptop and mobile slope coefficients are equal, it is assumed that intercept terms are equal, i.e., $â_{Djt} = â_{Mjt} = â_{jt}$ for all j=1,...,J characteristics, *and* $á_{Dt} = á_{Mt} = á_t$. In this specification, quality-adjusted price indexes are identical for desktop and mobile PCs. The corresponding fully restricted yearly hedonic price equation to be estimated takes the form

$$\ln P_{ijt} = á_t + Ó_j â_{jt} X_{ijt} + å_{ijt}. \tag{4}$$

B. PARAMETER STABILITY OVER TIME

An alternative dimension of parameter equality involves stability over time. To abstract from issues involving lack of parameter equality across classes of models, assume for the moment that based on results of hypothesis tests, we are dealing with a set of models over which the null hypothesis of either partial or full parameter equality has not been rejected, or, if partial parameter equality has been rejected, we are separately estimating cross-section hedonic price equations for desktop and mobile PCs. To keep our notation manageable, however, we now omit the D and M initial subscripts.

In the unrestricted adjacent time period regressions for time periods t and t-1, separate equations are specified for each time period:

$$\ln P_{ij,t-1} = á_{t-1} + Ó_j â_{j,t-1} X_{ij,t-1} + å_{ij,\,t-1}, \text{ and} \qquad (5)$$

$$\ln P_{ij,t} = á_t + Ó_j â_{j,t} X_{ij,t} + å_{ij,t}. \qquad (6)$$

In the common and widely used partially restricted adjacent time period regressions, it is assumed that each slope coefficient is equal (stable) in adjacent years, but that the intercept terms differ, i.e., $â_{j,t} = â_{j,t-1} = â_j$ for all j =1,...,J, but $á_t \neq á_{t-1}$. These parameter restrictions are frequently imposed by estimating adjacent time period hedonic price regressions having the form

$$\ln P_{ijô} = á_{t,t-1} + a_t T_t + Ó_j â_j X_{ijô} + å_{ijô}, \qquad (7)$$

where $P_{ijô}$, $X_{ijô}$ and $å_{ijô}$ are stacked vectors of observations for time periods t-1 and t, and since T_t is a dummy variable taking on the value of one if the observation is in time period t (else it is zero), a_t is the differential intercept for time period t relative to time period t-1, i.e., $a_t \equiv á_t - á_{t-1}$.

With this partially restricted adjacent year regression specification, frequently the quality-adjusted price index for year t relative to year t-1 is computed simply by exponentiating a_t.[9] When slope coefficients of more than two adjacent time periods are constrained to be identical while intercept terms are permitted to differ, quality-adjusted price indexes relative to the base time period are often computed using the sequence of exponentiated time period-specific intercept differentials, i.e., the sequence of $\exp(a_t)$, $\exp(a_{t+1})$, $\exp(a_{t+2})$, etc.[10]

Finally, in the fully temporally restricted hedonic price specification, it is assumed that not only are all slope coefficients in the adjacent time period regressions involving Eqns. (5) and (6) identical, but so too are the intercept terms, i.e., $\beta_{j,t} = \beta_{j,t-1} = \beta_j$ for all j = 1,,,,J, *and* $\alpha_t = \alpha_{t-1} = \alpha$, which implies that $a_t = 0$. The corresponding fully temporally restricted hedonic price equation is of the form

$$\ln P_{ij\tau} = \alpha + \Sigma_j \beta_j X_{ij\tau} + \varepsilon_{ij\tau}. \qquad (8)$$

When the constraints in Eqn. (8) hold, the quality-adjusted hedonic price index for time period t is the same as that for time period t-1.

One way of interpreting parameter inequality over time is in terms of neutral and non-neutral technological progress, as in the theory of cost and production. Specifically, in exponentiated (non-logarithmic) form, one can re-write Eqn. (6), allowing for time-varying elasticities, as

$$P_{ijt} = \alpha_t \bullet \Pi_j X_{ijt}^{\ \beta_{jt}} \varepsilon_{ijt} \quad . \qquad (9)$$

If the relationship between characteristics and price is time-invariant, i.e., if the β_{jt} elasticities are constant, or if technological change is characteristic-neutral, then one can rewrite Eqn. (9) as

$$P_{ijt} = \alpha_t \bullet \Pi_j X_{ijt}^{\ \beta_j} \varepsilon_{ijt} , \qquad (10)$$

which is analogous to the familiar Cobb-Douglas functional form.

C. HYPOTHESIS TESTING AND THE COMPUTATION OF QUALITY-ADJUSTED PRICE INDEXES

Hypothesis tests involving these various specifications can be carried out using the well-known Chow test under the assumption of i.i.d normality of the disturbance terms. Alternatively, one can compute standard errors using the White procedure that allows for heteroskedasticity, and then use as an estimate of the $(X'Ù^{-1}X)$ matrix that estimate obtained from the regression involving the null hypothesis.[11]

Consistent with the hedonic aggregation approach outlined in Triplett [1990b], we implement the sequence of hypothesis tests by first running yearly regressions separately for desktop and mobile PCs as in Eqns. (1) and (2), and testing whether the restrictions in Eqn. (3) are valid. If these restrictions are not rejected, we impose them, and continue on with various temporal stability tests. If the restrictions in Eqn. (3) are rejected, we do not impose them, and instead continue on with various temporal stability tests, separately for desktop and mobile PCs.

To assess parameter stability over time for the desktop and mobile PCs, we first estimate cross-sectional hedonic price equations for each pair of adjacent time periods, as in Eqns. (5) and (6), and then test whether the restrictions in Eqn. (7) are valid. If these restrictions are not rejected, we compute quality adjusted price indexes by chaining the sequence of estimated exponentiated a_t's, as discussed above. If, however, the parameter restrictions in Eqn. (7) are rejected, we compute various quality adjusted price indexes for successive time periods by employing parameter estimates from the separate adjacent time period cross-sectional regressions and computing predicted values based on alternatively the mean values of characteristics from time period t-1 (analogous to the base period quantity weights used in the Laspeyres index), from time period t (analogous to the current time period quantity weights used in the Paasche index), or their geometric mean (the Fisher Ideal index).

D. OTHER ISSUES REGARDING SPECIFICATION AND INTERPRETATION OF HEDONIC PRICE EQUATIONS

How one interprets estimated coefficients from hedonic price regressions has been the focus of considerable discussion in the literature.[12] Here, following Griliches, we envisage the hedonic price equations as being reduced form rather than structural, and therefore we do not interpret coefficients on characteristics as distinct measures of either consumers' marginal evaluations or producers' marginal costs, but rather as the outcome of consumer and producer optimization in the context of a differentiated product market. We note, however, that if characteristic quantities are viewed as being jointly determined, then even our relatively agnostic reduced form interpretation can be called into question.

At least since Ohta and Griliches [1986], there has been a literature comparing use of technical measures of characteristics (e.g., megahertz speed, hard disk capacity, and random access memory for computers, horsepower and weight for automobiles) with performance measures (e.g., millions of instructions executed per second for computers, or miles per gallon and acceleration for automobiles). In the context of computers, due in part to rapid technological progress, it has proven to be somewhat difficult to obtain system performance measures that are valid across models and over time.

A recent study by Chwelos [1999] is of particular interest in this context. Using a Delphi procedure, Chwelos first surveyed "power users" of PCs such as information system managers and business users concerning attributes of computer systems that provide value to users. He then developed an index of system performance measures based on data from published performance benchmarks. Chwelos also developed a set of technical proxy measures of system performance. Using data on IBM-PC compatible mobile and desktop systems, Chwelos found that both performance measures and technical measures yielded satisfactory explanatory power in hedonic price regressions and more importantly, that they yielded very similar estimates of the rate of quality-adjusted price change in PC systems. Hence in this study we will employ a set of technical characteristics as regressors in the hedonic price equations. However, since we allow the coefficients on these technical characteristics to vary across mobile and desktop PCs, and over time, we believe they provide an adequate proxy measure of varying PC system performance as well.[13]

IV. SUMMARY OF EXISTING RELEVANT LITERATURE

Chow's classic study of mainframe computers reported that quality-adjusted rental prices fell at an average annual growth rate (AAGR) of about -21% between 1960 and 1965. As regressors to adjust for quality change, Chow used a mix of performance and technical measures -- multiplication time, memory size and access time. Triplett [1989] reviewed a number of other hedonic studies on mainframe computers, and formed a "best practice" quality-adjusted price index; over the 1953-1972 time period, the AAGR of this index was about -27%.

In 1986 the IBM researchers Cole et al. [1986] published results of hedonic price analyses in which the individual components or "boxes" of a computer system were examined, rather than the system as a whole. For computer processors, Cole et al. found that over the 1972-84 time period, the AAGR based on hedonic prices was -19.2%, while that based on a "matched model" procedure in which one only compares prices on identical models observed in adjacent years was only -8.5%. The large discrepancy between matched model and hedonic measures reflects the inability of the matched model procedure to link in the effects of new models in the first year of their being on the market. Using similar procedures but aggregating over separate hedonic price equations involving computer processors, intermediate and large hard disk drives, printers and general-purpose displays, Cartwright [1986] reported an AAGR of -13.8% from 1972 to 1984; Cartwright's estimates, as well as the Ph.D. dissertation by Dulberger [1986], formed the basis of the BEA's new official price index for mainframe computers. Taking a longer historical view, Gordon [1989] estimates that a quality-adjusted mainframe price index for computers declined at an AAGR of -22% from 1951 to 1984.

To the best of our knowledge, the first hedonic studies involving PCs were the unpublished analyses by Cohen [1988] and by Kim [1989]. Cohen originally gathered price and characteristics data covering the 1976-87 time period; these data, which he updated to include 1988, were then examined further by Kim. Characteristics data collected by Cohen included RAM, MHZ, hard disk capacity, number floppy drives, number of slots available for expansion boards, and the age of the model. As reported in Berndt and Griliches [1993, Table 2.1], based on hedonic regressions, both Cohen and Kim found AAGRs ranging from -25% to -27% over the 1982-87 time period, while a BEA measure based on list prices and matched models declined at a considerably slower AAGR of about -17%. Interestingly, when Gordon [1990] used matched model procedures for 21 models observed between 1981 and 1987, based on transactions prices as advertised in Business Week and PC Magazine rather than list prices, he obtained a comparable AAGR of -23%.

Other hedonic price studies of PCs include those by Berndt and Griliches [1993] covering the 1982-88 time period, and by Berndt, Griliches and Rappaport [1995] over the years 1989-1992. Berndt and Griliches reported that although there was statistical support for parameter stability over time on characteristics regressors *within* the 1982-84, 1984-86 and 1986-88 time periods, *between* these time periods the null hypothesis of parameter stability on the characteristics regressors was typically rejected. Based on the hedonic price regressions, AAGRs of PCs over the 1982-88 time period ranged from about -23% to -25%, and were remarkably similar for list and discounted prices. When instead of using unweighted averages based on the hedonic regressions Berndt-Griliches used a Divisia index that incorporated quantity weights based on proprietary sales data sources, virtually identical AAGRs were obtained. However, the Divisia index revealed a smoother and less erratic decline than did the direct hedonic price indexes. Moreover, price declines of incumbent models were typically larger on average than those on entering and exiting models (about -27%, -22% and -17%, respectively).

In Berndt, Griliches and Rappaport [1995], a different data source is employed for the characteristics data, namely, DATAPRO, along with its list price data. When simple arithmetic means of prices are calculated over the 1989-92 time period, an AAGR of about -11% is obtained; this increases to about -19% when matched model procedures are employed. Berndt, Griliches and Rappaport distinguish mobile (transportable, notebook and laptop) models from desktops, but based on the limited number of mobile model observations and adjacent year regressions, they are not able to reject parameter stability (except for the intercept term), although the 1991-92 inference is marginal. For mobile models, the 1989-92 AAGR is -23.2% based on adjacent year regressions, and -23.9% based on a Divisia index with yearly parameters.

For desktop regressions, parameter stability on the characteristics regressions is decisively rejected in two of the three adjacent year regressions, and is marginal in the other (1990-91). Quality-adjusted price indexes have rather similar AAGRs across various specifications, however, ranging from about -31% to -32% between 1989 and 1992. Finally, when price indexes are first computed separately for desktops and mobile PCs, and then aggregated using Divisia weighting procedures, the combined desktop-mobile quality-adjusted price index declines at an AAGR of between 29-30% per year 1989-92, with a particularly large decrease in 1992.

Another PC hedonic price study is that by Nelson, Tanguay and Patterson [1994], based on IBM-PC compatible desktop-only models over the 1984-91 time period. Using list-price data and a number of technical characteristics variables, Nelson et al. report that yearly and adjacent-year regressions yield somewhat erratic results, although coefficients on characteristics variables typically decline in value over time, with a particularly large drop occurring in 1985-86. Using a nonlinear specification involving interactions between characteristics coefficients and time, Nelson et al. report quality-adjusted AAGRs for major manufacturers of about -17.5% between 1984 and 1991, and a larger -24.6% for mail order firms.

The final PC price study reviewed here is that by Chwelos [1999], which was mentioned and briefly discussed earlier. For mobile/laptop PCs, over the 1990-98 time period, no PC model was observed in more than one year, thus making the matched model procedure infeasible. Using benchmark measures of performance (based on Ziff-Davis Benchmark Operations and published in PC Magazine), Chwelos reports that laptop slope coefficient estimates were stable over time, suggesting that in terms of price/performance, these performance characteristics have been evolving at approximately the same rate, and that this rate was adequately captured by the time dummy variables. Exponentiating the time dummy variables, Chwelos obtained a quality-adjusted AAGR for laptops of around -39.6%. When Chwelos regressed his laptop processor performance index on a number of laptop technical characteristic variables (microprocessor, RAM, and cache dummy variables), he obtained an R^2 of 0.9819. It is not entirely surprising, therefore, that when Chwelos used as regressors the technical characteristic variables rather than the performance measures, the AAGR of the quality-adjusted price index was virtually identical at -40.0%.

For desktops, Chwelos' PC data are for the years 1992-98. The R^2 from a regression of desktop performance on technical characteristics variables was 0.9925, implying a very strong relationship between them. However, when performance measures were utilized as regressors, the AAGR of the quality-adjusted hedonic price index was about -32%, whereas that based on technical characteristics was slightly larger at about -35%.

V. ECONOMETRIC FINDINGS ON PARAMETER EQUALITY AND PARAMETER STABILITY

With this as background, we now report on econometric findings obtained from estimation of a variety of hedonic regression equations.

A. PARAMETER EQUALITY BETWEEN MOBILE AND DESKTOP MODELS

Mobile models have evolved considerably since their introduction in the early 1980s. Early mobile models were essentially suitcase-sized versions of desktop machines with a smaller screen replacing the desktop monitor, and as their "luggable" nickname implied, they could be lugged from place to place but only with some difficulty. With the advent of laptop computers in the late 1980s and notebooks in the 1990s, true computing portability was achieved. But this portability came with a cost. In exchange for lighter weight and smaller footprint came slower processor speeds, less memory, and less storage capacity, all at typically a premium price relative to a desktop with otherwise similar characteristics.

Nine luggable models first appear in our data set in 1983, increasing to 16 mobile models in 1984, 22 in 1985, 32 in 1986 and 73 in 1987; by 1999, we observe 1,165 distinct mobile models.

We estimate parameters in yearly regressions for 1983-99, first allowing for common slope coefficients for mobile and desktop models but a different intercept, as in Eqn. (3), and then allowing both for different intercepts and different slope coefficients, as in Eqns. (1) and

(2). Although the difference in 1983 intercept terms is insignificant, beginning in 1984 the difference between mobile and desktop intercepts is positive and statistically significant ($p < 0.05$), with the magnitude of the difference increasing over time. From 1984 through 1989, the mean difference in intercept terms is about 0.31, for 1990-93 it increases to about 0.43, then in 1994-96 it increases sharply to about 0.71, and in 1997-99 the mean difference in the mobile vs. desktop PC increases again to about 0.92. This implies that, when one constrains the characteristic coefficients (speed, hard disk capacity, memory, CD-ROM, Apple, and IBM-COM) to be the same across mobile and desktop PCs, in 1997-99 the price of a notebook computer was about 2.5 times that of desktop having the same technical characteristics.

For each year from 1983 onward, we then test the null hypothesis that the slope coefficients are equal across mobile and desktop models, against the alternative hypothesis that both slope and intercept terms differ. Ordinary least squares p-values from this test are plotted in Figure 2; the results allowing for heteroskedasticity are very similar. As is seen in Figure 2, except for 1983, beginning in 1987 and for each year thereafter (except 1997), we reject the null hypothesis of slope parameter equality between mobile and desktop PCs at p-values less than 0.05; for 1984-86, however, the null hypothesis is not rejected at this significance level. The general pattern, therefore, is that beginning about 1987 and continuing thereafter, the effects of changes in characteristics on prices differs between desktop and mobile models.

It is also of interest to examine which characteristic coefficients appear to differ between mobile and desktop models. To conserve space we do not report detailed results, but instead offer a brief summary. We find that in the mid to late 1990s, the estimated elasticity of price with respect to hard disk capacity is larger for mobile than desktop PCs, but the price elasticity with respect to speed is larger for desktops than mobile PCs.

In summary, the proportional price premium charged for mobile vs. desktop models has increased considerably from 1983 to 1999, and this price premium reflects in part a larger positive price elasticity with respect to hard disk capacity for mobile vs. desktop models, but a smaller price impact of speed. Coefficient estimates on characteristics differ significantly between mobile and desktop models, generally beginning in 1987 and continuing annually thereafter.

B. PARAMETER STABILITY OVER TIME

The null hypothesis of stability of all slope coefficients over time is decisively rejected, both for desktop and mobile PC models (p-value <0.001). Although it is possible to examine parameter stability over various lengths of time, separately for mobile and desktop models, we simplify the analysis here by assessing stability in successive pairs of adjacent year regressions.

As discussed above, because estimated slope coefficients for desktop and mobile PCs do not generally differ significantly until 1987, we first examine parameter stability for the pooled sample (but with a distinct mobile intercept) for years up to 1987. We find that up through 1987, in eight of the ten adjacent year pairs (all pairs except 1978-79 and 1983-84), we cannot reject the null hypothesis of all slope coefficients being equal in adjacent years.

Since mobile and desktop coefficients differ beginning in 1987, from 1987 onward we assess parameter stability separately for mobile and desktop PCs. For desktop PCs, as shown in Figure 3, in the twelve pairs of adjacent years between 1987 and 1999, the null hypothesis of slope coefficients being equal in adjacent years is rejected in all but one case (1990-91). However, as is seen in Figure 4, for mobile models the evidence on adjacent year slope coefficient stability is more mixed. Using a 0.05 significance level for each test, parameter stability is not rejected in five pairs of adjacent years (1988-89, 1989-90, 1990-91, 1992-93 and 1997-98), but is rejected in seven pairs of years, with a clear predominance in the later years (1987-88, 1991-92, 1993-94, 1994-95, 1995-96, 1996-97 and 1998-99). The pattern of inference is essentially unaffected when a heteroskedasticity-consistent disturbance variance-covariance is employed instead of that based on OLS estimation.

We interpret these findings as suggesting that in the desktop PC segment, particularly since the late 1980s there have been dramatic non-neutral changes in the relationships among technical characteristics and price. While there has also been enormous technological progress in the mobile PC market segment, apparently the nature of relationships among technical characteristics and prices has tended to have been a bit more neutral across characteristics than in the desktop PC segment, at least until recent years, and these changes are adequately captured by differential time intercepts.

Since presentation of all parameter estimates would take an enormous amount of space, in Table 1 we briefly summarize patterns of parameter change over time, separately for desktop and mobile PCs, over selected time intervals. In the first column of Table 1, we present parameter (elasticity) estimates based on the pooled over all years (1976-99 for desktops, 1983-99 for mobile) regressions, in which slope coefficients are constrained to be constant. The remaining columns of Table 1 are arithmetic means of parameter (elasticity) estimates from the adjacent year regressions over selected time intervals.

As seen in the top row of Table 1, the elasticity of price with respect to hard disk capacity was very high at about 0.38 when hard disks initially appeared on desktop PCs in the early 1980s, this elasticity dropped in half to about 0.19 in 1984-89, it dropped even further to about 0.05 in 1990-94, but particularly for mobile PCs it has increased sharply again during 1995-99. Recall that in the 1980s the early mobile PCs were luggable, in the later 1980s and early 1990s smaller but still rather heavy and cumbersome portables and laptops appeared, and finally the very thin and light notebooks have come to predominate in the late 1990s. In recent years space for hard disk capacity apparently commands a hefty premium in price in mobile PCs -- from 1995-99 the mobile elasticity of 0.36 is three times that for desktops at 0.12.

Trends in processor speed are quite different, as is seen in the second set of rows in Table 1. Since 1980 for desktop PCs, the elasticity of price with respect to speed has been larger than that for hard disks, and by the end of the 1990s the desktop elasticity of 0.72 is about twice that for mobile PCs at 0.34. The pooled regression estimate of 0.53 for desktops is considerably larger than the 0.33 estimate for mobile PCs.

Table 1

Mean Values of Elasticity Estimates on Characteristics Variables
Over Selected Time Intervals

Characteristic	Pooled Regression	Means from Adjacent Year Regressions 1976-79	1980-83	1984-89	1990-94	1995-99
Hard disk memory (ln mb)						
Desktop	0.09	na	0.38	0.19	0.05	0.12
Mobile	0.12	na	na	0.18	0.06	0.36
Processor speed (ln mhz)						
Desktop	0.53	0.19	0.40	0.69	0.53	0.72
Mobile	0.33	na	na	0.64	0.40	0.34
Active Memory (ln mb)						
Desktop	0.34	0.45	0.69	0.34	0.38	0.20
Mobile	0.26	na	na	0.32	0.08	0.21

Notes: Based on authors' regression analysis. na is not applicable.

Finally, in terms of RAM, as is seen in the bottom set of rows in Table 1, except for 1990-94, elasticities for mobile and desktop models are generally similar, and have fallen over time. For desktop PCs, the 1995-99 elasticity at 0.20 is less than 30% of its 0.69 value in 1980-83.

VI. ALTERNATIVE QUALITY-ADJUSTED PRICE INDEX CALCULATIONS

The econometric findings reported above for parameter equality between mobile and desktop PCs, and parameter stability over time, have implications for the construction and interpretation of quality-adjusted price indexes. We have constructed alternative price indexes that vary in the way they accommodate parameter inequality across desktop and mobile PCs, and instability in parameter estimates over time. Alternative results are presented in Table 2.

The simplest and most restrictive procedure is simply to pool observations across all years, restrict all slope coefficients to be constant over time, allow for a time-invariant dummy variable for mobile models, and specify yearly time dummy variables. Results from this simplest way to adjust PC prices for quality change are presented in Column 1 of Table 2. Under these assumptions, adjusted for quality changes, PC prices have fallen by a factor of 1000 from 1976 through 1999, implying an AAGR of -25.94%. Moreover, prices have declined at about twice the annual rate in 1994-99 relative to 1977-83 and 1983-99 (-38.72% vs. -18.00% and -17.68%, respectively).

A slightly less restrictive set of price index calculations involves maintaining the assumption of stability of all slope coefficient parameters over time, but separately estimating models for desktop and mobile PCs. Results from these calculations are given in Columns 2 and 3 of Table 2.

For desktop PCs, the 1976/1999 ratio of quality-adjusted prices is 1661:1, and over the shorter 1983-99 period it is 396:1. Over the entire 1976-99 time period, the AAGR is -27.46%, but this masks considerable intertemporal heterogeneity. From 1976 through 1989 the AAGR is a bit more than -18%, but this accelerates to about -34% from 1989 to 1994, and even further to -41% from 1994 to 1999.

Quality-adjusted price declines are considerable smaller in magnitude for mobile than desktop PCs, as one sees by comparing Columns (2) and (3). The 1983/99 ratio of quality-adjusted prices for mobile PCs is 40:1 (about one-tenth of that for desktops), reflecting an AAGR of -20.59%. Although mobile PC price declines were rather modest in the 1980s (around -8%), they picked up from 1989 to 1994 (-23%), and even more so in the late 1990s (-32%).

Table 2

Alternative Price Indexes Adjusted for Quality Change
(1983 = 1.0000)

YEAR	(1) ALL POOLED	(2) DESKTOP POOLED	(3) MOBILE POOLED	(4) DESKTOP ADJ/YEARLY LASPEYRES	(5) DESKTOP ADJ/YEARLY PAASCHE	(6) MOBILE ADJ/YEARLY LASPEYRES	(7) MOBILE ADJ/YEARLY PAASCHE
1976	4.0100	4.0671	na	6.7666	6.7666	na	na
1977	2.2819	2.2420	na	4.3807	4.3807	na	na
1978	1.9327	1.8969	na	3.7084	3.7084	na	na
1979	2.0035	1.9611	na	3.2008	3.2008	na	na
1980	1.9858	1.9440	na	3.0398	3.0398	na	na
1981	1.7825	1.7388	na	2.6154	2.6154	na	na
1982	1.4549	1.4040	na	1.8300	1.8300	na	na
1983	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1984	0.9967	0.9689	1.2390	0.8425	0.8425	0.8425	0.8425
1985	0.6757	0.6650	0.9490	0.5696	0.5696	0.5696	0.5696
1986	0.4773	0.4604	0.7363	0.3816	0.3816	0.3816	0.3816
1987	0.3624	0.3456	0.5878	0.2739	0.2865	0.2928	0.2928
1988	0.2658	0.2469	0.4633	0.1744	0.1957	0.2093	0.2093
1989	0.3111	0.2897	0.6084	0.1795	0.2165	0.2388	0.2388
1990	0.2631	0.2380	0.5231	0.1341	0.1735	0.2095	0.2095
1991	0.2315	0.2147	0.4780	0.1193	0.1627	0.1932	0.1932
1992	0.1069	0.0937	0.2426	0.0520	0.0682	0.1094	0.1094
1993	0.0843	0.0677	0.2558	0.0385	0.0568	0.1158	0.1158
1994	0.0464	0.0365	0.1664	0.0214	0.0445	0.0832	0.0907
1995	0.0328	0.0253	0.1188	0.0152	0.0425	0.0522	0.0702
1996	0.0206	0.0147	0.0932	0.0099	0.0335	0.0430	0.0462
1997	0.0135	0.0101	0.0651	0.0063	0.0202	0.0253	0.0343
1998	0.0055	0.0037	0.0327	0.0022	0.0113	0.0070	0.0096
1999	0.0040	0.0025	0.0250	0.0016	0.0113	0.0055	0.0064
AAGRs							
76-99	-25.94	-27.46	na	-30.44	-24.29	na	na
83-99	-29.17	-31.19	-20.59	-33.13	-24.45	-27.76	-27.07
76-83	-18.00	-18.16	na	-27.29	-27.29	na	na
83-89	-17.68	-18.66	- 7.95	-24.89	-22.51	-21.23	-21.23
89-94	-31.65	-33.93	-22.84	-34.65	-27.13	-19.01	-17.60
94-99	-38.72	-41.38	-31.56	-40.47	-24.02	-41.92	-41.15

Notes: Calculations based on authors' regression models. na is not applicable.

While provocative and intriguing, these price indexes adjusted for quality change depend on assumptions regarding parameter stability over time. Recall from our earlier econometric findings discussion that for slope coefficients in yearly regressions, significant differences between desktops and laptops generally began to appear in 1987, and continued thereafter. For desktops prior to 1987, the null hypothesis of parameter equality in pairs of adjacent year regressions was generally not rejected, and thus from 1976 to 1987 use of time dummies from desktop adjacent year time dummies is acceptable. However, the null hypothesis that desktop slope coefficients in pairs of successive adjacent year regressions from 1987-88 through 1998-99 were equal was rejected in eleven of twelve cases. To accommodate this parameter instability, we construct the analogs of Laspeyres and Paasche desktop price indexes beginning in 1987, using results from yearly desktop regressions. In particular, to construct a Laspeyres-type quality-adjusted price index between adjacent years t and t+1, we use parameter estimates from the separate year t and t+1 desktop regressions, we employ as "weights" the means of the desktop regressors in the "base" year t, and then take the ratio of predicted desktop prices in years t+1 and t. The analogous Paasche-type quality adjusted price index employs as quantity weights instead the means of the desktop regressors from the "current" year t+1. Results from these desktop calculations, linking adjacent year time dummies with Laspeyres and Paasche-type predicted price ratios, are given in Columns (4) and (5) of Table 2.

Comparing the desktop pooled (Column (2)), adjacent year/yearly Laspeyres (Column (4)) and adjacent year/yearly Paasche (Column (5)) price indexes, we observe a number of substantial differences. From 1976 through 1983, for example, use of adjacent year rather than pooled across year regression coefficients yields a considerably greater rate of price decline (AAGRs of -27.29% vs. -18.16%). This general differential pattern continues over the 1983-89 time frame, but the differences are not as dramatic.

Although there is a modest difference in 1983-89 AAGRs between the Laspeyres (-

24.51%) and Paasche (-22.89%) adjacent year/yearly indexes, the difference between them increases substantially in 1989-94 (-34.65% vs. -27.13%), and then diverges dramatically in 1994-99 (-40.47% vs. -24.02%). These differential estimates of quality-adjusted price decline are based on the same yearly regressions, and thus simply reflect the difference in "quantity" weights, weights that are changing very rapidly. Coincidentally, we believe, the AAGRs of Laspeyres adjacent year/yearly estimates in 1989-94 (-34.65%) and 1994-99 (-40.47%) are much closer to those of the temporally pooled desktop only indexes (-33.93% and -41.38%, respectively).

We now turn to evidence regarding quality-adjusted price declines for mobile PCs. Recall from above that econometric evidence on parameter stability over time indicated that use of adjacent year regressions is acceptable up through 1992-93, after which parameter estimates from yearly regressions are required. We have constructed Laspeyres- and Paasche-type mobile PC price indexes adjusted for quality change, with linked adjacent year and yearly mobile regressions, analogous to those for desktops. Results are given in the final two columns of Table 2.

The first striking finding is that when one compares the mobile Laspeyres and Paasche measures in Columns (6) and (7), unlike the case with desktops, the differences in AAGRs are relatively small. For 1989-94, the Laspeyres and Paasche prices have annual price declines of -19.01% and -17.60%, respectively, while in 1994-99 they are -41.92% and -41.15%. The second clear trend result is that, from 1983 to 1989, and 1989 to 1994, price declines are generally smaller for mobile than for desktop PCs; from 1994 onward, however, price decline trends are more similar. Third, it is also striking that when one compares quality-adjusted price indexes for mobile PCs using a temporally pooled mobile-only hedonic regression (Column (3) of Table 2), one generally obtains much smaller annual average price declines than when adjacent year/yearly regression equations are employed (Columns (6) and (7)); this is not always, the case, however, as is seen for the 1989-94 time period.

One clear lesson that emerges from this comparison, both for desktops and mobile PCs, is that the assumption of parameter stability over time on the characteristics variable is one that is empirically questionable at best, and has a very large and meaningful impact on the estimated rate of decline in quality-adjusted PC price indexes.

VII. CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

In this paper we have documented a quarter-century of technological progress in the US market for desktop and mobile PCs. Adjusted for quality change, we find that prices of PCs have fallen by about a factor of one thousand between 1976 and 1999, implying an AAGR of about -25%. Price declines have been larger in the 1990s than in the 1970s and 1980s, and have been larger in the late 1990s than in the early part of the decade.

The task of attempting to track quality-adjusted prices of goods when technological progress is so rapid and dramatic is a most difficult one. While hedonic methods are being employed increasingly by government statistical agencies, they frequently rely on assumptions regarding parameter stability over time, and equality across various sets of models. For PCs, we find that estimates of market price elasticities with respect to characteristics began to differ significantly in 1987 between desktop and mobile models, and continued to differ thereafter. Moreover, for desktop models, these elasticities differed even by year beginning in 1987, and for mobile PCs, beginning in 1993. For quality-adjusted price indexes to be reliable, such parameter variability needs to be accommodated. Unfortunately, parameter values do not appear to change monotonically with time, or across models, and thus it is not obvious how one might adapt parameter estimates based on data and hedonic price regressions that are several years old. Since parameter estimation of hedonic regression models is unlikely to be able to be done in real time, at least in the near future, an implication is that quality-adjusted price indexes for high-tech products such as PCs will likely only be available on a time-delayed basis.

It is worth noting that there are a number of important limitations to this research. First, list price data are used from 1989 onward, whereas from 1976 through 1988 a mix of list and transactions price data were available. Not surprisingly, in almost all our regressions we find a rather small and uncharacteristic quality-adjusted price increase between 1988 and 1989, which we believe likely reflects this price data transition, rather than a true price increase. Hence, "true" rates of price decline between pre- and post-1989 are likely to be even larger than estimated here.

Second, while a limited amount of quantity sales data for PCs was available from 1982-92, we have not been able yet to gain access to reliable sales data post-1992. Currently we are investigating possibilities of obtaining sales data that quantify sales by manufacturer and processor. While such a level of aggregation is less than ideal (numerous models from a manufacturer may have the same processor), it may provide some additional useful information. However, based on earlier research, we doubt use of sales data would fundamentally change our findings in any material manner.

Third, in an attempt to balance the benefits of additional technological detail with the possibility of somewhat erratic and volatile parameter estimates over time, we have limited our hedonic analysis here to a rather parsimonious set of specifications. In future research, we believe it will be important to examine the implications of relaxing the parsimonious parameterization assumptions.

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APPENDIX TABLE 1

MEAN PRICES AND VALUES OF SELECTED TECHNCIAL CHARACTERISTICS VARIABLES
ANNUALLY, 1976-1999, SEPARATELY FOR DESKTOP AND MOBILE MODELS

YEAR	NUMBER OF OBSERVATIONS	DOLLAR PRICE	HARD DISK CAPACITY - MB	RANDOM ACCESS MEMORY - MB	PROCESSOR SPEED - MHZ
DESKTOP MODELS ONLY					
1976	10	1897	0	0.00975	1.35
1977	17	1337	0	0.01245	2.06
1978	14	1136	0	0.01027	2.14
1979	26	1890	1.36	0.02093	2.29
1980	36	2025	1.44	0.02658	1.94
1981	38	2243	1.50	0.02948	2.41
1982	50	2388	1.53	0.05525	2.63
1983	76	2629	2.39	0.09912	4.07
1984	114	3015	4.30	0.17600	5.19
1985	92	3034	7.07	0.31443	5.89
1986	156	2757	10.79	0.48821	7.21
1987	324	2916	21.63	0.71086	9.43
1988	298	2992	40.46	0.93662	12.66
1989	173	4615	49.96	1.25225	15.63
1990	457	4426	61.89	1.79204	19.44
1991	322	4436	55.25	2.06353	21.18
1992	505	3399	132.48	5.19604	29.03
1993	943	2527	167.95	4.00502	34.15
1994	362	2031	721.99	5.45304	53.38
1995	476	2150	476.44	8.59644	78.04
1996	202	2593	1390.90	17.27418	140.50
1997	408	1985	1971.50	22.21414	184.28
1998	209	1466	5080.47	52.75000	337.00
1999	1247	1255	7105.97	69.75540	413.68

YEAR	NUMBER OF OBSERVATIONS	DOLLAR PRICE	HARD DISK CAPACITY - MB	RANDOM ACCESS MEMORY - MB	PROCESSOR SPEED - MHZ
			MOBILE MODELS ONLY		
1983	9	1961	3.00	0.10400	4.11
1984	16	2460	1.00	0.12950	3.70
1985	22	2159	1.86	0.16473	4.24
1986	32	2489	3.91	0.35125	5.62
1987	74	2416	7.74	0.44649	7.42
1988	58	2807	14.47	0.72166	9.87
1989	52	4616	29.10	1.14508	13.15
1990	118	4325	33.57	1.25278	14.37
1991	131	4037	33.44	1.25145	14.87
1992	125	3295	83.12	2.97312	22.75
1993	287	3303	99.56	3.06983	25.29
1994	248	3072	150.57	4.80460	40.75
1995	269	3317	365.18	5.88848	66.01
1996	123	4107	1012.44	11.64228	114.79
1997	79	3490	1383.92	15.64557	137.32
1998	131	3176	4445.04	45.06870	257.66
1999	263	2753	5545.20	55.98021	326.19

Footnotes

[1]Moore's law, originally enunciated by Intel cofounder Gordon Moore in 1965, postulated that the logic density of silicon transistors would double every year (he later changed this to 18 months). Although observers have often questioned the extent to which such progress can continue indefinitely without running into technological barriers, Moore's law is still widely thought to apply today. For recent discussions, see John Markoff [1999] and Charles Mann [2000].

[2]Of the ten 1976 PC models in our data set, one model had a speed of 0.5 MHZ, seven had 1 MHZ speed, one had a 2 MHZ speed, and the fasted a speed of 4 MHZ. Prices ranged from $375 to %5037. For other discussions of price and quality change in the PC market, see Cohen [1988], Kim [1989], Berndt and Griliches [1993], Nelson, Tanguay and Patterson [1994], and Stavins [1995].

[3]See Cartwright [1986], Cole et al. [1986], Dulberger [1989], Gordon [1989], and Triplett [1986]. For historical discussions, see Baily and Gordon [1988], Berndt [1991, Chapter 4], Griliches [1971, 1988] and Triplett [1990a].

[4]Sinclair and Caton [1990].

[5]See Fixler, Fortuna, Greenlees and Lane [1999] for further discussion; also see Armknecht, Land and Stewart [1997].

[6]Specifically, prices and models were taken from PC Magazine and New York Times, both in June of that year. Additional technical information came from Byte Magazine.

[7]Unfortunately, Datapro data are not available prior to 1989.

[8]For hard disk memory, the slope coefficient estimate is even larger at 0.4012 (R^2 of 0.9579), implying an AAGR of about 49% per year.

[9]As long as one is comparing ratios of predicted prices from adjacent year log-price regressions under the assumption of homoskedasticity, one can ignore the exponentiation of $0.5s^2$, where s is the standard error of the regression. Under heteroskedasticity, however, adjustments for the error variance are appropriate. See Berndt [1991], ch. 4, for further discussion.

[10]There are of course other more complex ways in which quality-adjusted price indexes can be computed based on estimated hedonic price equations. See Armknecht, Lane and Stewart [1997], Berndt [1991, Chapter 4], Berndt and Griliches [1993], Berndt, Griliches and Rappaport [1995], and Fixler, Fortuna, Greenlees and Lane [1999] for further discussion.

[11]Here Ù is the variance-covariance matrix of the disturbances. See White [1980]; also see Berndt [1991, Chapter 4].

[12]See, for example, Griliches [1971, 1988, 1990], Rosen [1974], Epple [1987], Triplett [1990a], Feenstra [1995] and Berry and Pakes [2000].

[13]For discussions of performance vs. technical measures in the context of semiconductors, see Holdway [2000] and Sliker [2000].

Figure 1
Personal Computers--1976-1999
Mean Prices, Mean Ln MHZ

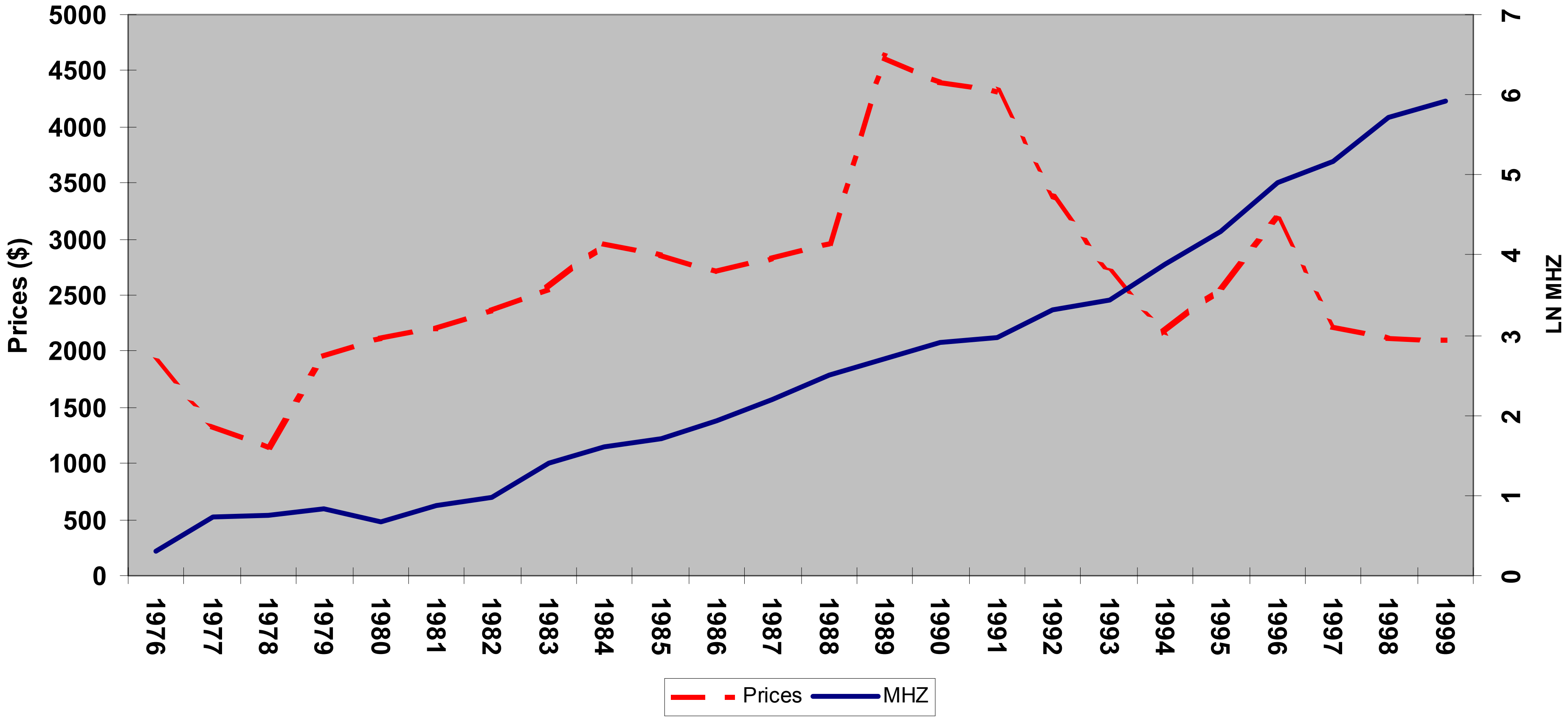

Figure 2
P-Values for Test of Slope Parameters for Portables
Ho: Slope Parameters Same as for Desktops

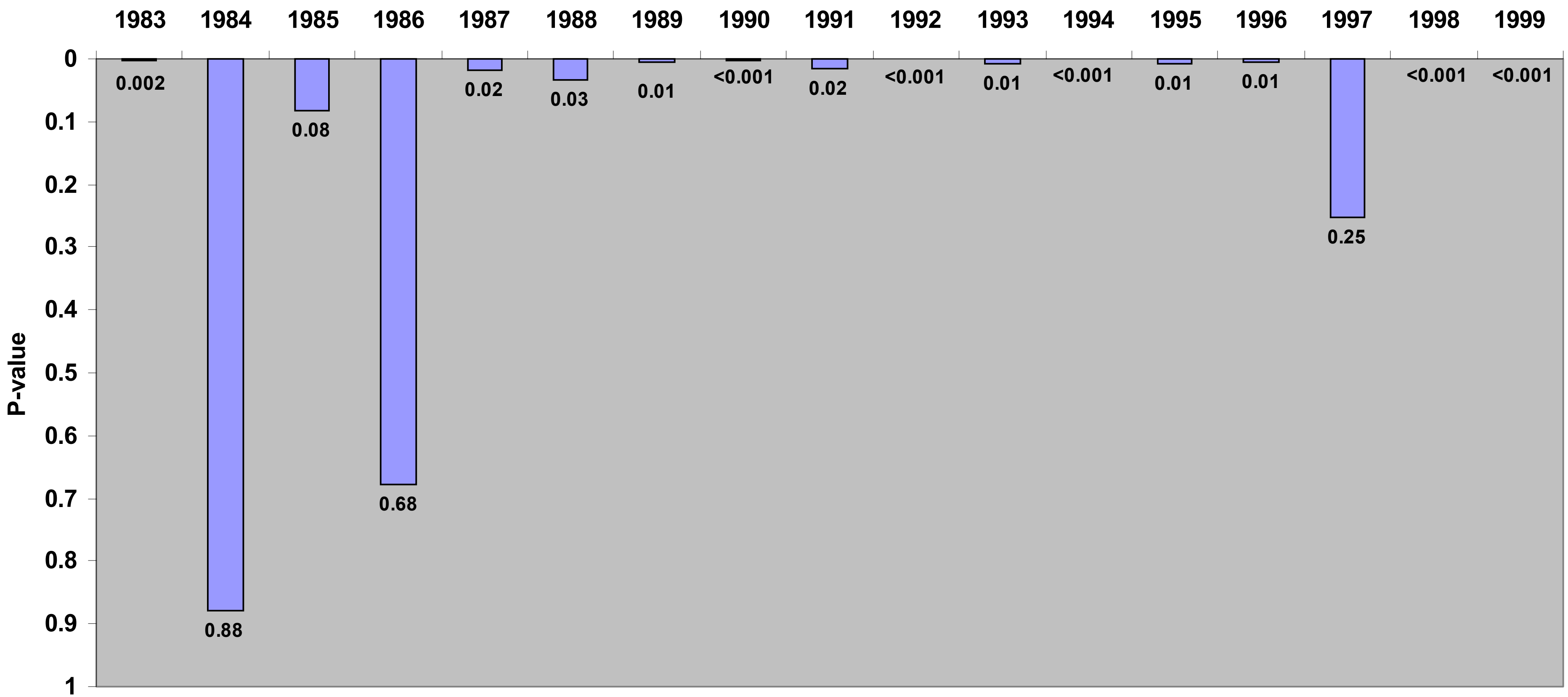

Figure 3
Desktop Computers: 1987-99--Adjacent Year vs. Yearly
Ho: Slope Parameters Equal Across Adjacent Years

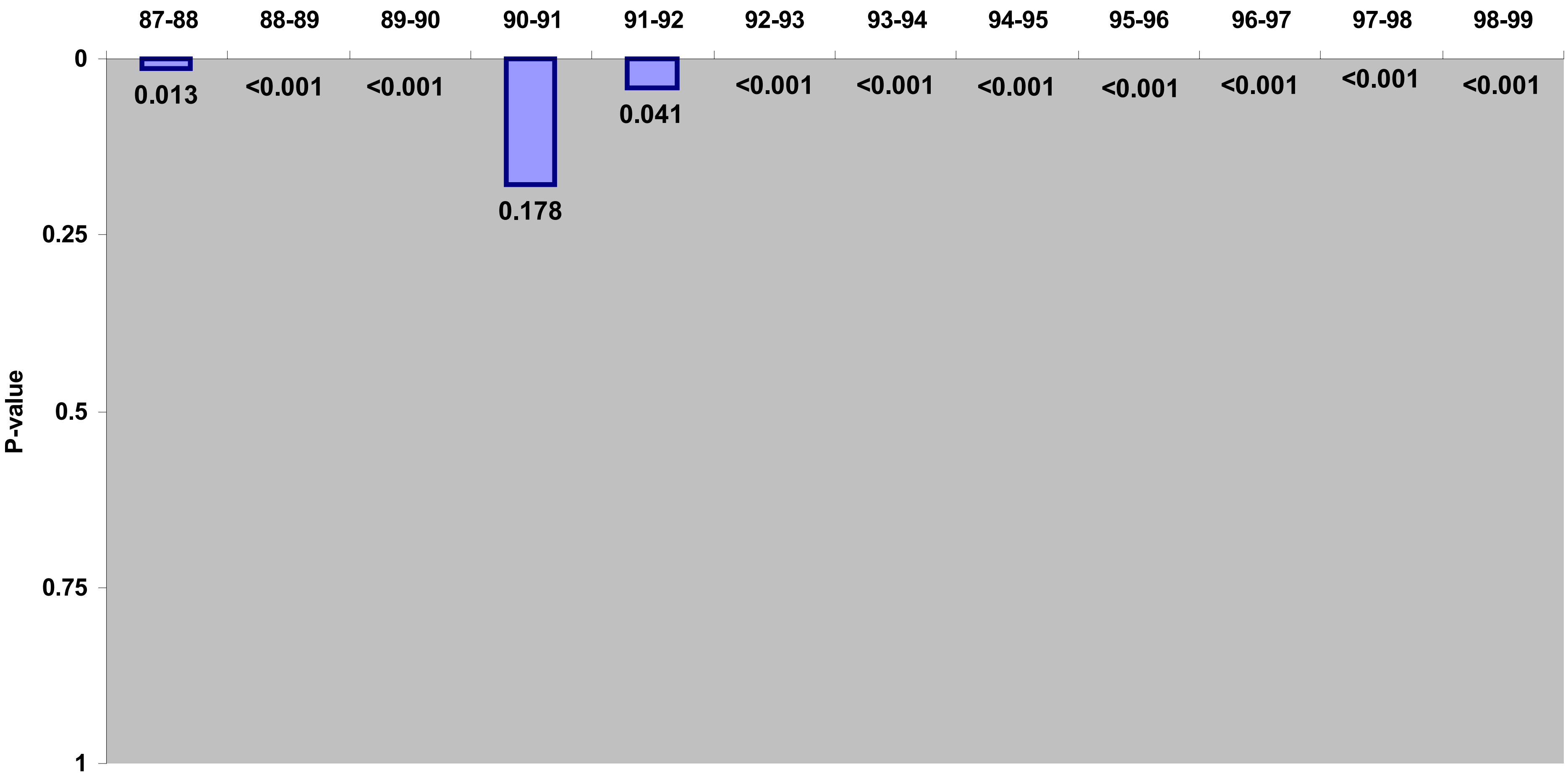

Figure 4
Portable Computers: 1987-99--Adjacent Year vs Yearly
Ho: Slope Parameters Equal Across Adjacent Years