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Effects of Quality Changes on the Price Index: A Hedonic Approach to the Estimation of a Quality Adjusted Price Index for Personal Computers in Japan

SHIGENORI SHIRATSUKA

This paper studies the effects of quality changes on Japan's CPI by estimating a quality adjusted price index (hedonic price index) for discounted personal computers during 1990-94. According to the result, quality adjusted prices for personal computers in Japan have declined at an annual rate of 20-25% since 1990, reducing consumer durable CPI by 0.2% points per annum and overall CPI by 0.01% points. As consumer durables are apt to be affected by constant quality improvements, this result suggests that the conventional price index for consumer durables is likely to have substantially underestimated real declines in prices.

Key Words: Hedonic Price Index; Personal Computers; Measurement Errors; Quality Changes

I. Introduction

This paper studies the effects of quality changes on the price index, or the extent of their inflation bias, by estimating a quality adjusted price index for personal computers. It first presents the theory and methodology of the so-called "hedonic approach," and then applies this to the estimation of a quality adjusted price index for discounted personal computers during 1990-94.

Measurement errors and inflation bias in conventional price indexes are becoming important topics of discussion in Japan. For example, some argue that CPI (Consumer Price Index) has failed to capture the deflationary effects of what the Japanese press has termed "price destruction" which refers to the phenomenon of substantial price declines due to the emergence of many discount stores and roadside retailers, as well as the appearance of low-priced special brand items sold at supermarkets. They point to the observation that CPI (excluding fresh food) has risen amidst widespread "price destruc-

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tion." In response, the Ministry of International Trade and Industry (MITI) and the Economic Planning Agency (EPA) have published the findings of their own research on major CPI items concerning price differences among department stores, supermarkets, specialty shops, and discount stores. Seiyu, a major supermarket chain, has also published its own consumer price index, the "Seiyu Price Index" based on its merchandise goods.

The possible causes of measurement errors in the price index are "sampling errors," "quality adjustments," "fixed weights" as well as the treatment of "imputations" and "indirect taxes." At this point, I will focus on the issues of "sampling errors" and "quality adjustments" in the presence of so-called "price destruction" leaving the other issues of measurement errors as topics for future research.

The "sampling errors" refer to a failure to include new discount stores and low-priced special brand products in the sample for the price index. The problem is how to select a representative basket of goods that would reflect a general price movement in a changing market environment. The problem of "quality adjustments" refers to the difficulty in judging whether the goods sold at discount stores and those sold at department stores are of the same quality, as well as whether the clothes sold this season and the clothes sold last season are of the same quality. The problem is how to incorporate quality differences between old and new products in the price index.

Of these two problems, recent discussions about the accuracy of the price index have focused more on the problem of "sampling errors" rather than on the problem of "quality adjustments." However, the problem of "quality adjustments" is becoming a major source of inflation bias in the markets characterized by rapid technological change. Furthermore, the problem of "quality adjustments" also arises when we attempt to correct a "sampling error" by incorporating a new product sold at discount stores: correcting a "sampling error" gives rise to a need to take into account quality differences between the goods sold at new discount stores and those sold at conventional stores included in the sample. In short, we cannot avoid the problem of "quality adjustments" whenever we change items in the sample basket to capture a changing market environment. Such "specification changes" replacement of individual prices surveyed, are becoming increasingly important for constructing a more accurate price index.[1]

It is important for the accuracy of a price index to continuously make appropriate quality and sampling adjustments so that it can capture structural changes like the phenomenon of "price destruction" and technological innovation. In practice, however, those products whose quality changes are difficult to measure are often excluded from price index baskets. In fact, personal computers, which are known for their rapid quality changes, are not included in the basket for current CPI, which takes 1990 as its base year.

[1]Bank of Japan Price Index Study Group (1992) discusses the methodology of constructing a price index, which includes these "specification changes."

This is because the market for personal computers is characterized by a rapidly changing environment such as continuous technological innovation and intense foreign competition, particularly with the recent entry of DOS/V personal computers. Such a changing market environment makes it very difficult to construct and update a quality adjusted price index within the framework of the conventional price index methodology.

This paper adopts the "hedonic approach" to construct the price index and attempts to overcome the problem of "quality adjustments." The "hedonic approach" was first introduced by Court (1939) who applied it to constructing a price index for the U.S. car market. Court named his new price index "hedonic" because he wanted to capture in his index the various characteristics of the car that provide the consumer with pleasure and comfort.

The "hedonic approach" is based on the assumption that the quality of a product is determined by its objective characteristics and therefore the quality of a product can be measured as an aggregation of those objective characteristics. There are some shortcomings in this approach. First, application is limited to products for which information about their objective characteristics is readily available. Second, the cost of constructing such an index may be substantial. Nevertheless, its greatest advantage is that a quality adjusted price index can be constructed based on objective characteristics of a product without relying on subjective judgment about its quality. Moreover, once a hedonic function is estimated, all that we need for making quality adjustments later on is information about price and characteristics of the product. This is the greatest advantage of a "hedonic price index" for products like personal computers which have a short product cycle and experience frequent quality improvements.

The rest of the paper is organized as follows: Section II presents the basic framework of the "hedonic approach" for constructing a quality adjusted price index, and introduces the results of several empirical researches conducted in Japan and the United States. Section III estimates a "hedonic function" for personal computers, using advertised prices of personal computers at discount stores in Japan. Furthermore, it calculates a quality adjusted "hedonic price index" for personal computers since 1990, and estimates the effects of incorporating the hedonic price index in CPI. According to this result, quality adjusted prices for personal computers in the Japanese discount market have declined at an annual rate of 20-25% since 1990, reducing consumer durable price index by 0.2% points per annum and overall CPI by 0.01% points. As consumer durables are apt to be affected by constant quality changes, the fact that the index declined 0.2% every year with the incorporation of the quality adjusted computer price index suggests that the conventional consumer durable price index is likely to have substantially underestimated real declines in the prices of consumer durables.

II. Theoretical Framework of the Hedonic Approach

A price index should be generally understood as a quality adjusted price index that measures a price change in a basket of goods over time while keeping their qualities constant at the level of the base year. A question arises as to how to define the quality that must be kept constant. It becomes a serious problem for goods like a personal computer, which experienced rapid technological innovation, to find an appropriate method to measure price change while keeping quality constant. This section briefly discusses the methodology of the "hedonic approach" for constructing a quality adjusted price index and the consumer theory called the "Lancaster model" which provides a theoretical foundation for the "hedonic approach." Finally, it provides a brief survey of empirical applications of the "hedonic approach."

A. Hedonic Approach to Quality Estimation

The hedonic approach assumes that the price of a good exchanged in markets depends on the characteristics of that good. This approach is theoretically based on the so-called "hedonic hypothesis" which regards the quality of a good as an aggregation of those characteristics.

Consider the meaning of quality that is determined by characteristics. According to Ohta (1980), the quality of a good has two meanings: first, the objective level of each characteristic that provides utility to consumers and, second, the overall evaluation of such characteristics. In the case of a personal computer, the former quality can be expressed as a combination of physical characteristics such as processing speed, main memory size, auxiliary storage capacity that can be found in a computer catalog. Therefore, computers that have the same physical characteristics are considered to be of the same quality. However, to deal with the problem of changing quality in the price index, it becomes necessary to measure quality in the sense of the overall evaluation of objective characteristics of a good. That is, in the case of a personal computer, it becomes necessary to aggregate various characteristics of a computer in a single index so that we can measure a quality difference between two computers. The "hedonic approach" makes it possible to express the common characteristics by a monetary value because a price of a good is assumed to depend on the overall level of performance characteristics.[2]

A new consumer theory known as the "Lancaster model" provides a theoretical foundation for the "hedonic approach."[3] Figure 1 shows the main difference between the

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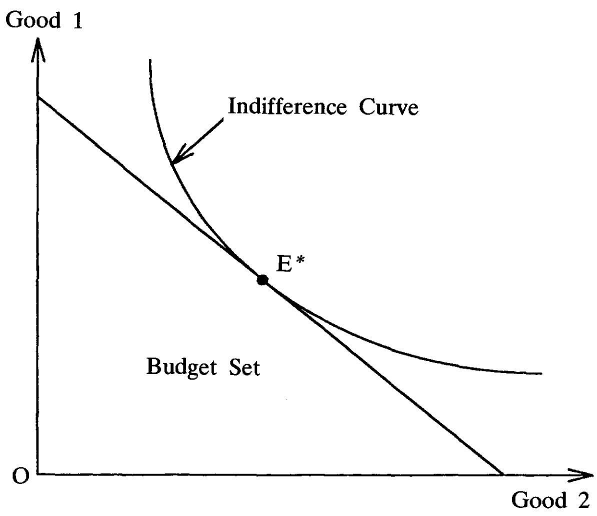
[2]Mathematically the hedonic approach can be written as follows: let C^i be an n-dimensional vector of characteristics of good i, and p^i the price of good i. Then the hedonic approach states that the price of a good is a function of those characteristics, that is, $p^i=h(C^i)$.

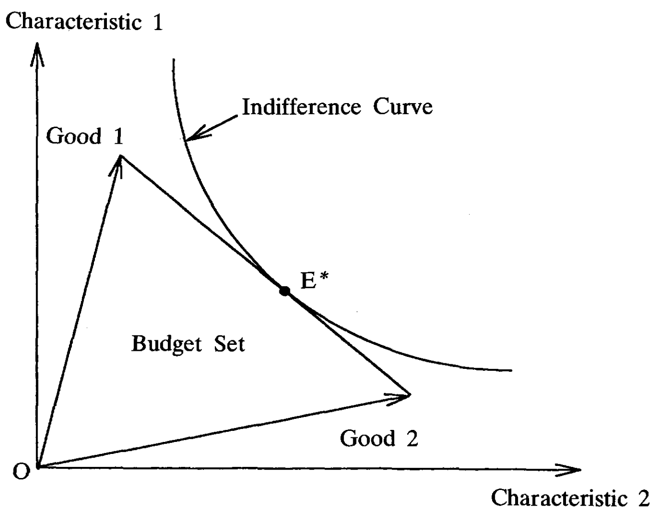
[3]From rational consumer behavior of the Lancaster model, we can derive a hedonic function $p^i=h(C^i)$ which relates the price to the characteristics of a good. See Appendix A. See also Lancaster (1991) and Ohta (1980) for a general discussion about the Lancaster model.

Figure 1
Consumer Equilibrium

A. Consumer Equilibrium in the Conventional Microeconomic Model



B. Consumer Equilibirium in the Lancaster Model



Lancaster model and the conventional microeconomic model of consumer behavior. The conventional microeconomic model treats two goods as different goods if they have slightly different qualities; in other words, the same goods have an identical quality. In Figure 1-A, substitutable goods 1 and 2 are considered as two different goods, and consumer preferences are defined on a vector of the quantities of good 1 and good 2. Point E*, at which the budget line and an indifference curve are tangent to each other, becomes consumer equilibrium. The assumption that the number of goods and their qualities are given may be reasonable as a first approximation to the reality. But, it becomes problematic when applied to the modern economy in which quality changes and product differentiation are important economic phenomena.

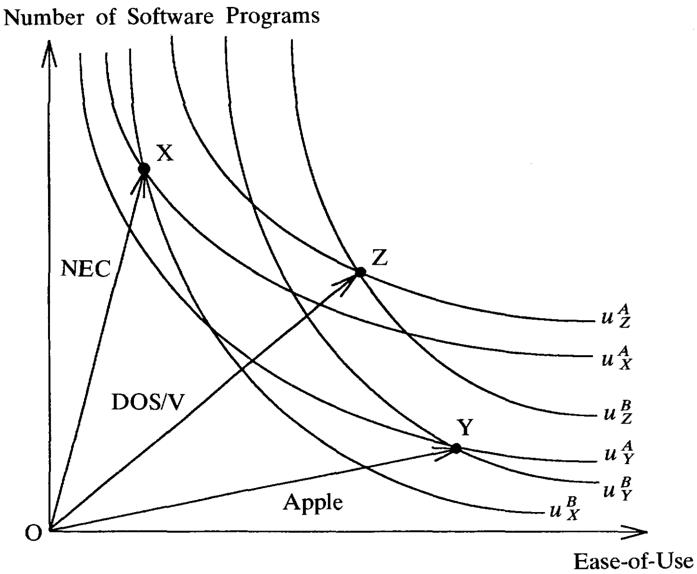
In contrast, to deal with the issue of quality changes and product differentiation, the Lancaster model assumes that consumer preferences are defined on a vector of characteristics of goods enjoyed by the consumption of those goods, rather than the amounts of goods consumed themselves. Figure 1-B shows that goods 1 and 2 are decomposed into characteristics 1 and 2, and the goods are defined as a combination of those two characteristics. In this example, it is assumed for brevity that there are only two goods in the economy. Therefore, the length of a vector of a good becomes equivalent to consumer income divided by the price of that good. The consumer budget set becomes a triangle spanned by the vectors of those two goods. Consumer preferences are defined on a vector of characteristics and consumer equilibrium is obtained at point E* where the budget set and indifference curve are tangent to each other. Thus, the Lancaster model makes it possible to deal with the phenomenon of product diversification and the differentiation of substitutable goods as well as the emergence of new products.

Figure 2 applies this approach to the recent expanded sale of DOS/V personal computers in Japan. For simplicity, it is assumed that the characteristics of the computer consist of the number of applications and ease of use. It is also assumed that the prices of computers are all identical. The economy is assumed to consist of two types of consumers: type A consumers place more value on the number of software applications and therefore have indifference curves with mild slopes; type B consumers place more value on ease of use and therefore have indifference curves with steep slopes.

Now suppose that type A and type B consumers plan to purchase a personal computer. Their problem is to choose only one computer out of several existing computers in the economy. In other words, it is assumed that goods are indivisible. This assumption is different from that in Figure 1-B where goods are assumed to be infinitely divisible.[4] The Japanese personal computer market, before the appearance of DOS/V computers, was characterized by the existence of two major types of computers: NEC-type computers which have many software applications but are inferior in terms of ease of

[4]As a result, the budget set consists of the end points of product vectors (**X**, **Y**, and **Z** in Figure 2) instead of a triangle in Figure 1-B.

Figure 2
Application of the Lancaster Model
(Analysis of Market Expansion of DOS/V Computers)



use (vector **OX**), and Apple-type computers which have fewer software applications but an advanced ease-of-use capability (vector **OY**). Here, consumers choose a computer that gives them the greatest utility, comparing **X** and **Y**. Therefore, a consumer who values the number of software applications (type A) will choose an NEC computer or point **X** ($U_X^A > U_Y^A$), while a consumer who values ease of use (type B) will choose an Apple computer or point **Y** ($U_X^B < U_Y^B$). When DOS/V computers which have a relatively large number of software applications and high ease-of-use have appeared in the market, both type A and B consumers have shifted to a DOS/V computer or point **Z**, which gives a higher utility than points **X** and **Y** ($U_Z^A > U_X^A$, $U_Z^B > U_Y^B$). As a result, the demand for personal computers has shifted from NEC and Apple computers to DOS/V computers, forcing the former two to produce new products with an improved performance/price ratio.

B. Previous Empirical Research

Empirical research has taken the form of estimating a regression equation with observed prices as a dependent variable and quality characteristics as independent explanatory variables with a constant and an error term.[5] Many empirical studies on

[5]See Appendix A for a general discussion of the theoretical foundation of the hedonic approach. As a hedonic function represents the supply-demand equilibrium of product characteristics in the market, there is no

personal computers conducted in the United States have used log-transformed variables as follows:

$$\ln p_{it} = \alpha + \sum_{j=1}^{n} \beta_j \ln x_{ijt} + \sum_{k=1}^{T} \delta_k d_{ikt} + u_{it}$$

where x_{ijt}, d_{ikt}, and u_{it} *represent a* j-th characteristic of the i-th good at period t, a k-period dummy variable, and an error term, respectively.

The first empirical application of the hedonic approach was taken by Court (1939) who studied the U.S. automobile market. Since then, along with new theoretical developments, many applications have been effected not only for automobiles, but also for consumer durable goods like refrigerators and for capital goods like boilers.[6] The recent applications of the hedonic approach in the United States are for mainframe and personal computers,[7] as well as for apparel products which are then incorporated in CPI.[8] In addition, an increasing number of applications extending to service prices have been conducted in Japan.[9] These recent studies are summarized in the Supplementary Table attached at the end of this paper. Since the 1990-base year revision of wholesale price indexes in 1992, further studies have been conducted in applying the hedonic approach to price indexes for personal computers, mainframe computers, and magnetic disk equipments in the Bank of Japan.[10]

III. Empirical Application of the Hedonic Approach to the Personal Computer Market in Japan

This section applies the hedonic approach to the estimation of a hedonic function for the personal computer market in Japan, and then constructs a quality-adjusted price index for personal computers. Next, it studies the extent to which incorporating this quality-adjusted index will affect overall CPI.

A. Data

This paper uses the discount market prices and functional characteristics of personal computers obtained from the following data sources: computer prices are obtained from

particular functional form that is correct *a priori*. It is appropriate therefore to choose a functional form that is most convenient in practice. See Appendix B for further discussion on this point.

[6]See Ohta (1980) and Berndt (1991) for a comprehensive survey of the theoretical and empirical studies concerning the hedonic approach.

[7]For a general survey, see Jorgenson and Landau (1989), Foss, Manser, and Young (1993).

[8]See Liegey (1993).

[9]See Sawa *et al.* (1989), Ito and Hirono (1993), and Suzuki and Ohta (1994).

[10]These studies have adopted a different method from that adopted in Section III: this paper calculates a price index directly from an estimated hedonic function while they used previously estimated shadow prices of characteristics for quality adjustments when sample items for the wholesale price index are changed. Moreover, they used "list prices" available directly from producers, also different from this paper's method.

the monthly computer magazine "*ASCII*" (June issues from 1990 to 1994) which contains advertised prices of computers sold in the Tokyo area.[11] The functional characteristics of computers are obtained mainly from "*Nikkei Data Pro EDP*" and some are obtained directly from producers.

"*ASCII*" has a long publication history and contains a large number of computer advertisements. This makes "*ASCII*" a superior source of historical price data among many personal computer magazines. "*Nikkei Datapro EDP*" contains many evaluations of performance characteristics of computers as well as detailed description of their functions.

Some caution, however, is in order. First, the price data from "*ASCII*" represents the asking prices for computers by discount stores and therefore are not necessarily the same as the prices at which actual transactions are made. Moreover, there are cases in which the prices of some models are advertised as special "telephone prices" which are not made public.[12] Therefore there may remain some questions as to whether or not the prices listed in "*ASCII*" are indeed representative market prices and free from any bias.[13]

Second, because prices and functional characteristics are obtained from two different data sources, actual consumers are not necessarily making their purchasing decisions based on the same information about functional characteristics as the one used in this study. This point however may be understood as follows: the present empirical tests are a joint test of the validity of the hedonic approach and the validity of informational efficiency in the personal computer market. In other words, if the explanatory power of the hedonic approach is high, it implies that consumers are making their purchasing decisions based not only on information in magazine advertisements but also on additional information they have obtained from computer catalogs, computer experts, and magazine articles which provide objective performance evaluations.

The above potential problems originate from the use of the advertisements in magazines as our price data sources, and they need to be taken into account in evaluating

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[11]The computer prices used in this paper are "set prices" which include monitors. This is because advertisements are often for a computer set, and also because notebook and even some desktop models include a monitor as part of the computer body. Accordingly, a monitor price is added to the computer price when an advertised price excludes a monitor to make it comparable. Although the back issues of "*ASCII*" before 1990 contain price data before 1990, most of the advertisements in those issues are for NEC computers and the number of advertisements declines sharply. Accordingly, the data set contains price data back to base year 1990.

[12]Even if the "telephone prices" were obtainable, they should be excluded from the data set because they are used as "attractions" or a means of bringing more customers to the store, and therefore are likely to be biased downward.

[13]Nevertheless, these problems with the "*ASCII*" data are unlikely to be serious because the data set includes many discount stores in the Tokyo area such as "Sofmap" and "Step," and also because the empirical results of this paper appear to be very reasonable.

the empirical results obtained from those data.[14]

B. Specification of Functional Characteristics

In the estimation of a hedonic function, it is important to use explanatory variables as those characteristics of a product that have high power in explaining product price. Generally, those characteristics depend on technical factors pertaining to the product. In theory, the characteristics that enter into a hedonic function should be "performance variables" directly related to the performance of the product (speed, comfort, handling, etc. in the case of a car); but, in practice, the characteristics that are readily available are "physical variables" (horse power, displacement, weight). On this point, Ohta (1980) has statistically verified that "physical variables" worked well as good substitutes for "performance variables" in the case of a car. It is reasonable to believe that the same conclusion will hold in the case of a personal computer, which is the subject of the present empirical research.

Therefore, among the functional characteristics that have been used in past research conducted abroad, and are mentioned in computer magazine articles, the variables listed in Table 1 are chosen as explanatory variables in the hedonic function in this paper.

Table 2 shows the basic statistical data for the above functional characteristics as well as computer prices. The movement of annual average figures in the table clearly reflects the rapidly changing market environment that has been caused by such events as the participation of foreign producers with DOS/V personal computers and technological innovation that have improved the performance/price ratio. Continuous improvements in the main characteristics of personal computers such as clock frequency, memory, hard disk capacity, expansion slots, and display density, have occurred in recent years, and the speed of such improvements has accelerated particularly since 1993. Moreover, the share of high performance computers has risen as indicated by increases in the value of functional dummy variables (for example, the CPU type has shifted from 8 and 16 bits to 32 bits). While performance has improved, the average price has declined at an annual rate of 3%. As a result, the performance/price ratio has improved substantially. It is also noteworthy that the share of foreign producers of DOS/V computers has risen sharply while that of NEC, which dominated the Japanese market before 1992, has fallen.

C. Estimation Results of a Hedonic Function

The estimation of a hedonic function has been conducted for three different sample data: the full sample regression using all the sample data in 1990-94, the 2-year sample regression using 2-year sample data, and the 1-year sample regression using 1-year

[14]The same potential problems were pointed out by Ito and Hirono (1993) who analyzed residential prices and rents using the data from advertisement in housing magazines.

Table 1
Functional Characteristics as Explanatory Variables in Hedonic Function

Variables	Units	Characteristics
Clock Frequency	MHz	processing speed of the CPU
Memory	MB	standard memory size
Hard Disk	MB	standard hard disk capacity
Number of Expansion Slots	unit	the number of channels for expansion slots
Screen Density	square of thousand dots	maximum monitor screen density
Type Dummy		differentiation between desktop, laptop, and notebook
Monitor Dummy		monochrome CRT, color CRT, plasma LCD, monochrome LCD, STN color LCD, TFT color LCD
CPU Type Dummy		8 bits, 16 bits, 32 bits (Pentium and others), power PC (RISC chip)
FD Drive Dummy		1 with more than 2 FD drive, and 0 with 1 FD drive or less
CD-ROM Dummy		1 with CD-ROM, and 0 for without
Sound Function Dummy		1 with a sound board, and 0 without
Windows Preinstalled Dummy		1 with preinstalled Windows, and 0 without
Large Display Dummy		1 with 17 inch or larger display, and without
Company Dummy		a company dummy with NEC as a standard base

Table 2
Basic Statistics for Characteristics of Personal Computers

	Annual Average					All Sample	
	1990	1991	1992	1993	1994	Average	Average Rate of Change
Price (thousand yen)	367.750	491.450	407.160	343.060	323.770	380.260	-3.134
Clock Frequency (MHz)	14.125	18.194	18.706	29.430	43.857	27.341	32.743
Memory (MB)	1.230	1.927	2.879	4.847	6.265	3.918	50.225
Hard Disk (MB)	20.357	30.867	56.762	118.650	230.670	109.090	83.472
Expansion Slot	2.036	2.112	2.365	2.303	2.599	2.334	6.293
Screen Density (thousand dots^2)	275.650	342.150	382.570	455.870	551.460	427.010	18.929
Desktop	0.643	0.551	0.611	0.669	0.673	0.634	
Laptop	0.286	0.184	0.008	0.000	0.000	0.062	
Notebook	0.071	0.265	0.381	0.331	0.327	0.304	
Monochrome CRT	0.054	0.051	0.024	0.000	0.000	0.019	
Color CRT	0.589	0.500	0.587	0.669	0.673	0.615	
Plasma LCD	0.036	0.020	0.008	0.000	0.000	0.009	
Monochrome LCD	0.304	0.388	0.333	0.239	0.170	0.274	
STN Color LCD	0.018	0.020	0.000	0.014	0.054	0.023	
TFT Color LCD	0.000	0.020	0.048	0.077	0.102	0.060	
8 bits	0.107	0.000	0.000	0.000	0.000	0.011	
16 bits	0.446	0.276	0.079	0.000	0.000	0.109	
32 bits	0.446	0.724	0.921	1.000	0.952	0.868	
Pentium	0.000	0.000	0.000	0.000	0.048	0.012	
Power PC	0.000	0.000	0.000	0.000	0.054	0.014	
FD Drives (more than 2)	0.786	0.561	0.421	0.345	0.313	0.434	
CD-ROM	0.000	0.000	0.008	0.092	0.231	0.084	
Sound Function	0.000	0.000	0.000	0.000	0.082	0.021	
Windows Preinstalled	0.000	0.000	0.008	0.056	0.483	0.141	
Large Display	0.000	0.122	0.008	0.049	0.034	0.044	
Number of Samples	56	98	126	142	147	569	100.0
NEC	31	52	52	44	53	232	40.8
Epson	17	17	23	19	17	93	16.3
Toshiba	5	11	13	9	15	53	9.3
Fujitsu	0	6	5	3	7	21	3.7
Apple	3	12	25	26	15	81	14.2
IBM	0	0	8	15	6	29	5.1
IBM Compatible	0	0	0	26	34	60	10.5

sample data.[15] The reason for conducting three estimations for different sample data is to check the stability of estimated parameters, which represent the shadow prices of functional characteristics of the personal computer. Those parameters might have been affected by rapid technological innovation during the sample period.

Table 3 summarizes the estimation results of the hedonic functions, which indicate high reliability for each sample period. The coefficient of determination exhibits a high value for three different sample data. The signs of estimated five parameters for clock frequency, memory, hard disk capacity, expansion slots, and display density are all positive and generally statistically significant. Dummy variables also exhibit expected signs. The estimated parameters show time-series movements reflecting technological innovation; in particular, the parameter for hard disk capacity has declined sharply since 1992-93, and that for display density declined sharply in 1994. These movements are consistent with the recent declines in hard disk and graphic board prices.[16] In contrast, the parameters for memory and expansion slots exhibit relatively stable movements without any apparent trends.

The estimated parameters for company dummies represent price differentials which reflect company differences in technological strength, quality of services, availability of software programs, etc., which are omitted from the specified functional characteristics ("omitted characteristics").[17] For example, the decline in the parameter for the Apple Computer Company dummy in 1993-94 reflects the fact that it has lost some of its non-price competitive edge because of the debut of Windows in 1993, even though Apple had a strong non-price competitive edge before 1992-93, reflecting the advanced ease-of-use capacity of Macintosh OS. The estimated parameters for Compaq and Dell, which started to enter the Japanese market with their DOS/V computers in 1993, are somewhere between -0.2 and -0.4, which means that their DOS/V computers are 20-40% cheaper than NEC computers with the same functional characteristics. Thus, NEC computers are still sold at higher prices. This may partly reflect some "omitted characteristics", like the availability of a large number of software programs, which give rise to price differentials.

From 1990 to 92, before the introduction of DOS/V computers, the fit of the hedonic function is very good for both regressions with the 1-year and 2-year sample with a coefficient of determination at 0.9 or higher. Since 1993, however, the coefficient of determination has fallen, particularly for the regression with the 2-year sample. This implies that the Japanese computer market has been experiencing rapid and often discontinuous structural changes since the entry of foreign competitors with DOS/V

[15]The estimation used LIMDEP version 6.0. The standard deviations are adjusted for the effects of heteroscedasticity in accordance with White (1980).

[16]The graphic board transforms computer signals to video signals which a monitor can read. It significantly affects the quality and speed of display picture and color.

[17]See Ohta (1980) for discussion on the effects of "omitted characteristics."

Table 3
Estimatioin Results of Hedonic Function

		Full Sample Estimation	2-Year Sample Estimation 1990-91	1991-92	1992-93	1993-94
Constant		3.2022 (0.191 *)	1.5987 (0.297 *)	2.5321 (0.352 *)	2.5426 (0.210 *)	3.0759 (0.258 *)
Clock Frequency		0.3210 (0.035 *)	0.5827 (0.092 *)	0.3734 (0.097 *)	0.3881 (0.044 *)	0.3937 (0.029 *)
Memory		0.0654 (0.015 *)	0.0775 (0.017 *)	0.0632 (0.018 *)	0.0510 (0.020 *)	0.1109 (0.019 *)
Hard Disk		0.0567 (0.005 *)	0.0824 (0.006 *)	0.0817 (0.008 *)	0.0524 (0.007 *)	0.0314 (0.005 *)
Expansion Slot		0.2436 (0.035 *)	0.1272 (0.035 *)	0.3198 (0.046 *)	0.1728 (0.055 *)	0.2212 (0.041 *)
Screen Density		0.2693 (0.030 *)	0.4008 (0.037 *)	0.3181 (0.040 *)	0.3107 (0.032 *)	0.1428 (0.040 *)
Type	Laptop	0.2272 (0.042 *)	0.1758 (0.031 *)	0.2371 (0.042 *)	0.1244 (0.072**)	( )
	Notebook	0.1048 (0.048**)	0.0143 (0.058)	−0.0596 (0.066)	0.1040 (0.070)	0.2774 (0.062 *)
Monitor	Monochrome CRT	−0.2587 (0.111**)	−0.0290 (0.116)	−0.4661 (0.119 *)	−0.8149 (0.136 *)	( )
	Plasma LCD	0.3165 (0.200)	0.5682 (0.111 *)	0.0632 (0.154)	−0.4141 (0.053 *)	( )
	STN Color LCD	0.3994 (0.058 *)	0.2765 (0.095 *)	0.0551 (0.033**)	0.3136 (0.131 *)	0.2939 (0.044 *)
	TFT Color LCD	0.5608 (0.038 *)	0.4495 (0.031 *)	0.3950 (0.035 *)	0.4784 (0.058 *)	0.4764 (0.036 *)
CPU	8 bits	−0.2699 (0.076 *)	−0.0207 (0.100)	( )	( )	( )
	16 bits	−0.1982 (0.038 *)	0.0091 (0.050)	−0.0951 (0.053**)	−0.3827 (0.085 *)	( )
	Pentium	0.2137 (0.061 *)	( )	( )	( )	0.3450 (0.037 *)
	Power PC	−0.0911 (0.072)	( )	( )	( )	0.0445 (0.080)
FD Drive (more than 2)		0.0460 (0.038)	0.1392 (0.042 *)	−0.0658 (0.057)	0.1302 (0.066**)	0.0274 (0.043)
CD-ROM		−0.0419 (0.047)	( )	0.3679 (0.031 *)	0.1487 (0.069**)	0.1014 (0.043 *)
Sound Function		−0.0450 (0.066)	( )	( )	( )	−0.0341 (0.061)
Windows Preinstalled		−0.0926 (0.045**)	( )	0.1866 (0.039 *)	0.1656 (0.074**)	−0.0234 (0.035)
Large Monitor		0.4583 (0.066 *)	0.6154 (0.052 *)	0.6227 (0.060 *)	0.1810 (0.059 *)	0.2039 (0.043 *)
Year	1991	−0.1882 (0.037 *)	−0.2113 (0.026 *)	( )	( )	( )
	1992	−0.3650 (0.043 *)	( )	−0.1877 (0.031 *)	( )	( )
	1993	−0.6697 (0.044 *)	( )	( )	−0.3839 (0.036 *)	( )
	1994	−0.9259 (0.051 *)	( )	( )	( )	−0.3393 (0.027 *)
Maker	Acer	−0.7733 (0.060 *)	( )	( )	( )	−0.5926 (0.059 *)
	Apple	0.2484 (0.054 *)	0.3746 (0.083 *)	0.2754 (0.069 *)	0.2501 (0.070 *)	0.0451 (0.062)
	Compaq	−0.2685 (0.043 *)	( )	( )	−0.2924 (0.064 *)	−0.2079 (0.033 *)
	DEC	−0.5108 (0.096 *)	( )	( )	−0.3495 (0.079 *)	−0.2637 (0.042**)
	Dell	−0.4376 (0.051 *)	( )	( )	−0.3660 (0.078 *)	−0.3476 (0.045 *)
	Epson	−0.1733 (0.023 *)	0.0115 (0.027)	−0.1585 (0.034 *)	−0.3292 (0.035 *)	−0.1748 (0.035 *)
	Fujitsu	−0.1495 (0.063 *)	0.2134 (0.065 *)	−0.0494 (0.069)	−0.2050 (0.084 *)	−0.1267 (0.082**)
	IBM	−0.2233 (0.051 *)	( )	−0.1740 (0.049 *)	−0.2246 (0.064 *)	−0.2331 (0.052 *)
	Packard Bell	−0.5272 (0.040 *)	( )	( )	−0.6692 (0.056 *)	−0.3784 (0.054 *)
	Toshiba	−0.1424 (0.053 *)	−0.1027 (0.055**)	−0.1320 (0.050 *)	−0.2363 (0.070 *)	−0.1200 (0.037 *)
Adjusted R^2		0.7955	0.9553	0.9058	0.7761	0.7917
Sum of Squared Residuals		26.1014	2.3067	7.2160	11.0360	6.9486
Number of Samples		569	154	224	268	289

Note: Standard errors are in ( ); * and ** indicate statistical significance at 1 and 5% level, respectively.

Table 3
Estimation Results of Hedonic Function (continued)

		1 Year Sample Estimation									
		1990		1991		1992		1993		1994	
Constant		1.4009	(0.312 *)	2.0623	(0.488 *)	2.0325	(0.415 *)	1.7475	(0.315)	3.1472	(0.291 *)
Clock Frequency		0.5791	(0.125 *)	0.5028	(0.102 *)	0.6437	(0.152 *)	0.4000	(0.040**)	0.4006	(0.036 *)
Memory		0.0869	(0.031 *)	0.1195	(0.017 *)	0.0597	(0.028**)	0.1309	(0.024**)	0.0729	(0.023 *)
Hard Disk		0.0740	(0.010 *)	0.0933	(0.006 *)	0.0686	(0.009 *)	0.0292	(0.006 *)	0.0390	(0.007 *)
Expansion Slot		0.0661	(0.055)	0.1931	(0.041 *)	0.4643	(0.084 *)	0.1478	(0.059**)	0.1306	(0.051 *)
Screen Density		0.4377	(0.047 *)	0.3096	(0.062 *)	0.2163	(0.046 *)	0.3551	(0.052**)	0.1019	(0.044**)
Type	Laptop	0.1478	(0.052 *)	0.1280	(0.035 *)	0.2878	(0.068 *)		( )		( )
	Notebook	−0.1310	(0.089)	0.0739	(0.073)	0.0017	(0.095)	0.3912	(0.082**)	0.1608	(0.076**)
Monitor	Monochrome CRT		( )	−0.1694	(0.121)	−0.6091	(0.162 *)		( )		( )
	Plasma LCD	0.5805	(0.148 *)	0.5452	(0.080 *)	−0.2943	(0.055 *)		( )		( )
	STN Color LCD	0.4784	(0.039 *)	0.1297	(0.038 *)		( )	0.1972	(0.102)	0.2615	(0.048 *)
	TFT Color LCD		( )	0.4158	(0.042 *)	0.3533	(0.054 *)	0.4461	(0.042**)	0.4689	(0.047 *)
CPU	8 bits	−0.0131	(0.122)		( )		( )		( )		( )
	16 bits	0.0660	(0.073)	−0.0286	(0.057)	−0.0410	(0.089)		( )		( )
	Pentium		( )		( )		( )		( )	0.3497	(0.038 *)
	Power PC		( )		( )		( )		( )	0.2339	(0.116**)
FD Drive (more than 2)		0.1735	(0.085**)	0.1323	(0.036 *)	−0.0397	(0.072)	0.1973	(0.068**)	0.0406	(0.041)
CD-ROM			( )		( )	0.2461	(0.035 *)	0.2527	(0.071**)	0.0217	(0.046)
Sound Function			( )		( )		( )		( )	0.0951	(0.071)
Windows Preinstalled			( )		( )	0.1077	(0.047**)	0.1361	(0.055**)	−0.0064	(0.042)
Large Monitor			( )	0.6621	(0.083 *)	0.5623	(0.059 *)	0.2730	(0.058**)	0.2283	(0.037 *)
Maker	Acer		( )		( )		( )		( )	−0.5234	(0.066 *)
	Apple	0.6135	(0.100 *)	0.2923	(0.082 *)	0.2895	(0.084 *)	0.1406	(0.073**)	−0.1649	(0.107)
	Compaq		( )		( )		( )	−0.2734	(0.052**)	−0.2024	(0.042 *)
	DEC		( )		( )		( )	−0.3326	(0.073**)	−0.2611	(0.042 *)
	Dell		( )		( )		( )	−0.3498	(0.063**)	−0.3701	(0.051 *)
	Epson	0.0526	(0.045)	0.0441	(0.036)	−0.2616	(0.049 *)	−0.3677	(0.061**)	−0.1802	(0.038 *)
	Fujitsu		( )	0.1709	(0.069 *)	−0.2597	(0.064 *)	−0.0366	(0.162)	−0.2265	(0.074 *)
	IBM		( )		( )	−0.1413	(0.066**)	−0.2226	(0.067**)	−0.4171	(0.072 *)
	Packard Bell		( )		( )		( )	−0.6137	(0.073**)	−0.3059	(0.054 *)
	Toshiba	0.0227	(0.111)	−0.1613	(0.059 *)	−0.1941	(0.073 *)	−0.2386	(0.056**)	−0.0755	(0.043**)
Adjusted R^2		0.9418		0.9710		0.8860		0.8191		0.8574	
Sum of Squared Residuals		0.4812		1.1210		3.5760		2.5792		2.3188	
Number of Samples		56		98		126		142		147	

Notes: 1. Standard errors are in ( ); * and ** indicate statistical significance at 1 and 5% level, respectively.

2. The 1990 company dummy for Apple includes Monochrome CRT (because all Apple computers have Monochrome CRT but not).

computers.[18]

Finally, let us check the stability of estimated parameters using a statistical method. The F test rejects the null hypothesis that the estimated parameters are the same through the 5-year sample period: the F statistic turns out to be 8.642 which compares to the critical value of 1.302 at the 5% significance level. The stability of estimated parameters is thus rejected. This, however, may be partly due to a sampling problem in addition to the effects of technological innovation. That is, the data set contains only 16 continuous computer models, which has continuously existed more than 2-year sample period, and the type (desktop, laptop, notebook) and maker have changed substantially over time. In fact, the estimated parameters for the 1-year regression show substantial variations around a gradual downward trend, while those for the 2-year regression show less variations. The latter is less likely to be affected by sample bias.

D. Calculation of a Hedonic Price Index

Table 4 shows the calculated hedonic price indexes (1990=100) using the estimation results of the hedonic function for personal computers (see Appendix C for calculation method). The hedonic price indexes are calculated for the results of three different sample period estimations: the full sample period, the 2-year sample period, and the 1-year sample period, all of which exhibit a downward trend. The price index for 1994 is calculated at 39.6 for the full sample period, 32.6 for the 2-year sample period, and 37.4 for the 1-year sample period, which implies an average annual decline of 20-25%. In

Table 4
Movements in Hedonic Price Indexes for Personal Computers

						Rate of Change	
	1990	1991	1992	1993	1994	Annual	Cumulative
Average Price	100.0	133.6	110.7	93.3	88.0		
(Rate of Change, %)		33.6	−17.1	−15.7	−5.7	−3.1	−12.0
Full Sample Estimation	100.0	82.8	69.4	51.2	39.6		
(Rate of Change, %)		−17.2	−16.2	−26.2	−22.7	−20.7	−60.4
2-Year Sample Estimation	100.0	81.0	67.1	45.7	32.6		
(Rate of Change, %)		−19.0	−17.1	−31.9	−28.8	−24.5	−67.4
1-Year Sample Estimatiion	100.0	79.3	61.6	40.8	37.4		
(Rate of Change, %)		−20.7	−22.3	−33.8	−8.3	−21.8	−62.6

[18]See Oniki (1994) for an analysis of price movements in the Japanese personal computer market.

contrast, the average prices without quality adjustments rose in 1991 and then fell with the overall average annual decline of 3% during the same period.

These results suggest the risk of misjudging true price movements if we look only at a price index that does not incorporate quality adjustments. This risk would be greater for goods with rapid quality improvements like personal computers.

The sharp decline in the hedonic price index in 1992-93 coincides with the entry of Compaq and Dell into the Japanese market with their DOS/V personal computers and NEC responding by changing its pricing strategy. This development is consistent with another estimation result where the parameters of company dummies of these DOS/V computers have statistically significant minus signs.

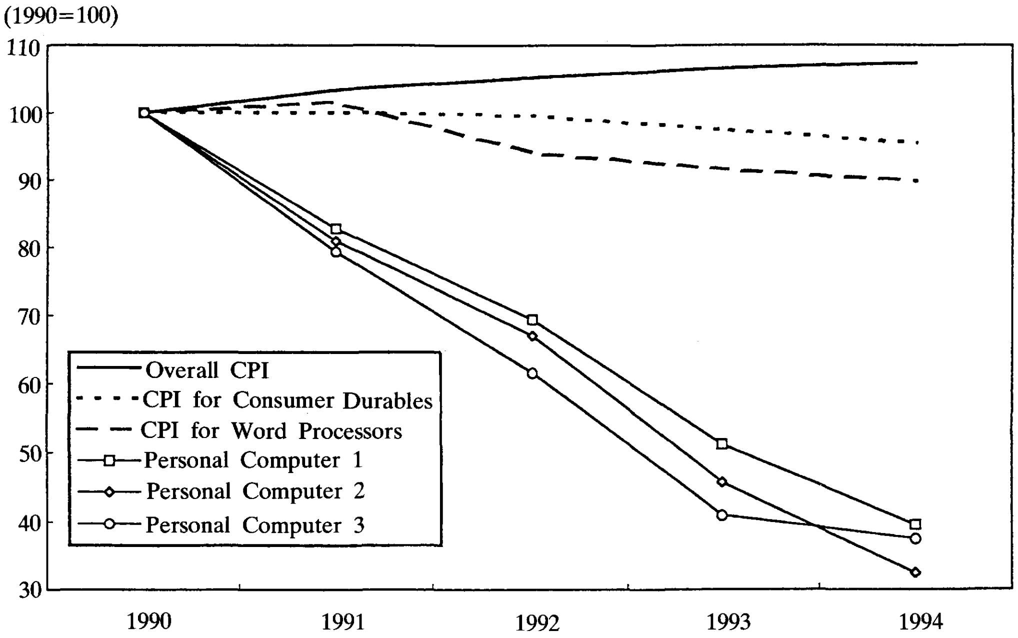
Next, we consider which is the best price index for personal computers among the three indexes based on the full, 2-year, or 1-year sample period estimation. First, as we have seen, the full period estimation apparently suffers from the problem of structural shifts in estimated parameters due to rapid technological innovation. Second, the 1-year period estimation also suffers from the problem of sample data bias: the composition of sample data has changed substantially year to year, and the parameters are evaluated by the average values of characteristics at the base year of 1990 for caliculation of hedonic price index. On the other hand, the 2-year period estimation seems to suffer less from shifts in parameters and sample data bias. Therefore, the 2-year period estimation results will be used in the following as the quality adjusted price index for personal computers.

Figure 3 plots the movements of the CPI (Tokyo) for overall goods, consumer durables, and word processors, in addition to the three hedonic price indexes for personal computers. Comparing difference in price movements of these indexes, we can confirm particularly sharp price drops for personal computers. Next, let us examine the effect of the quality adjusted computer price index on CPI. At present, personal computers are not included in the basket for 1990-base CPI and therefore recent sharp drops in computer prices are not reflected in current CPI. The effects of incorporating the estimated hedonic price indexes for personal computers into the CPI are summarized in Table 5.[19]

[19]Table 5 assumes that half of the weight for word processors is replaced by the weight for personal computers. In the present CPI system, personal computers are not treated as an independent item but "word processors" are. The CPI weights are based on the *Kakei Chosa* (Family Income and Expenditure Survey), which reports total expenditures on word processors and personal computers without distinguishing between them. Thus, in accordance with the general treatment of CPI weight calculation, the weight for "word processors" (0.17% in Tokyo) is divided equally between word processors and personal computers in the present calculation.

The assumption of equal weights for word processors and personal computers is also consistent with the following observation. First, as listed in *ASCII* magazine, the average price for personal computers in 1990 was about 368,000 yen (Table 2) while the average price for word processors, calculated from the advertised prices in the "*ASCII*", was 124,000 yen. Second, as reported in the Economic Planning Agency's *Shohi Doko Chosa* (Current Consumer Survey), 2% of households bought a personal computer and 6% a word processor in 1990. It thus follows that total expenditures on word processors and personal computers were approximately equal.

Figure 3
Movements in Hedonic Price Indexes for Personal Computers



Note: Personal computers 1, 2, and 3 represent the estimated hedonic price index for full, 2-year, and 1-year sample data, respectively.

Table 5
Effects of Inclusion of Hedonic Price Indexes

	1991	1992	1993	1994	Rate of Change Annual	Rate of Change Cumulative
Overall CPI (Tokyo)						
Full Sample	−0.016	−0.005	−0.013	−0.008	−0.011	−0.042
2-Year Sample	−0.017	−0.006	−0.016	−0.010	−0.012	−0.048
1-Year Sample	−0.019	−0.009	−0.017	−0.002	−0.011	−0.044
Durable Goods CPI (Tokyo)						
Full Sample	−0.311	−0.099	−0.261	−0.163	−0.208	−0.830
2-Year Sample	−0.341	−0.113	−0.327	−0.215	−0.237	−0.946
1-Year Sample	−0.369	−0.184	−0.348	−0.039	−0.217	−0.866

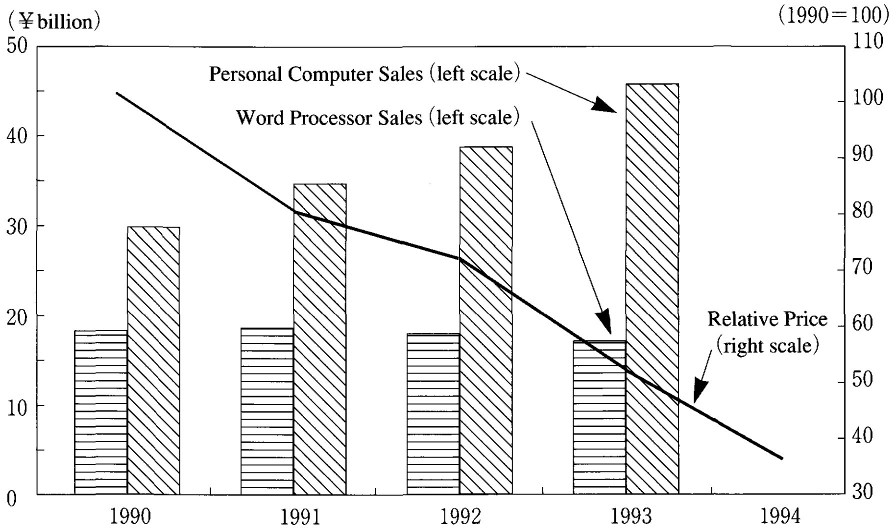
Note: Estimated on the assumption that half of the weight for word processors (17/10,000) in CPI is replaced by personal computers.

According to the table, incorporating the prices of personal computers has the effect of reducing the durable goods CPI by 0.2% points per annum and overall CPI by 0.01% points.

As the durable goods CPI is most likely to be affected by technological innovation, the fact that it has fallen by 0.2% points per annum with incorporation of the personal computer price index implies that the durable goods CPI may have seriously underestimated actual price declines. Since micro-electronic products like personal computers are greatly affected by technological progress and have a shorter product cycle than other durable goods, the problem of quality adjustment seems more serious for them. This means that it is difficult to maintain the continuity of product specifications in the price index basket. Therefore, introduction of new products in this area to the price index basket tends to be delayed. In fact, word processors were not included in CPI until the 1990-base and, moreover, personal computers are still not included.

Finally, to check the validity of the hedonic price index, Figure 4 plots the total sale values and relative prices of personal computers and word processors, which are con-

Figure 4
Sales and Relative Prices for Personal Computers and Word Processors



Sources: *Consumer Prices Index*, Management and Coordination Agency; *Sales of Electric Products*, Nippon Electoric Bigstores Association.

Note: The relative price is the radio of the estimated hedonic price index (2 -year sample estimation) for personal Computers to CPI (Tokyo) for word processors.

sidered to be close substitutes.[20] According to the figure, sales of word processors have remained stagnant while those of personal computers have risen, and, at the same time, the relative price of personal computers has declined substantially. This suggests that consumers have been substituting personal computers for word processors in response to the recent declines in the relative price of computers.

IV. Conclusion

This paper has focused on quality adjustments (one of the main issues in the measurement problems with respect to price indexes), applying the hedonic approach to the Japanese discount market for personal computers, and calculating a quality adjusted hedonic price index for personal computers. The hedonic index indicates that the price of personal computers in the discount market has declined at the average annual rate of 20-25% since 1990, which would have reduced durable goods CPI by 0.2% points per annum and overall CPI by 0.01% points. From a practical viewpoint, the hedonic approach has proven to be a very effective method *vis-à-vis* quality adjustment for constructing a reliable price index.

Despite the efforts of many statistical institutions in constructing accurate statistics, measurement errors are unavoidable to some extent. Thus, the most important point is to ascertain whether they are small enough to be safely ignored in practice or serious enough to mislead users. The debate about the accuracy of CPI should therefore be aimed at investigating the sources of measurement errors and the extent to which they affect accuracy. Unfortunately, research on price index measurement errors has been limited in Japan, and further research in the area is necessary.

Appendix A: Theoretical Foundation of the Hedonic Approach

This appendix gives the theoretical foundation of the hedonic approach, which is based on the "new consumer theory", called the "Lancaster model". In particular, adopting the arguments of Rosen (1974), it shows how a hedonic function can be derived as an equilibrium price function, matching demand for and supply of differentiated products, in a hypothetical market for the characteristics of differentiated products.

Let a vector of characteristics $\boldsymbol{z} = (z_1, z_2, \ldots, z_n)$ represent a differentiated good defined by those characteristics. From an observed price for good, one can derive a hedonic function $p(z) = p(z_1, z_2, \ldots, z_n)$, which relates the price to those characteristics. It is assumed that there is a sufficiently large number of goods so that one can choose any good as a continuous combination of those characteristics.

[20]In calculating relative prices, the hedonic price index based on the 2-year sample period estimation was used for computer prices and CPI for the word processor prices.

Consider the following consumer's utility maximization problem: let $\boldsymbol{z}$ stand for a vector of characteristics to be consumed, and x for a numeraire good. Then the utility function can be written as $U(\boldsymbol{z}, x)$. The budget constraint for a consumer with income y can be written as $y = p(\boldsymbol{z}) + x$. Now the consumer is assumed to be a price taker and solve the following maximization problem:

$$\max_{\boldsymbol{z}} \quad U(\boldsymbol{z}, x) \qquad \text{s. t.} \quad y = p(\boldsymbol{z}) + x \tag{A-1}$$

The first-order condition for this problem is:

$$p_{\boldsymbol{z}} = \frac{U_{\boldsymbol{z}}(\boldsymbol{z}, y - p(\boldsymbol{z}))}{U_x(\boldsymbol{z}, y - p(\boldsymbol{z}))} \tag{A-2}$$

where $p_{\boldsymbol{z}}$, $U_{\boldsymbol{z}}$, and U_x are first-order partial derivatives.

Next, for a bid function for utility level u, $\theta(\boldsymbol{z}; u, y)$, the following relationship holds:

$$U(\boldsymbol{z}, y - \theta) = u \tag{A-3}$$

Differentiating equation (A-3), we obtain:

$$\theta_{z_i} = U_{z_i}/U_x > 0 \tag{A-4a}$$

$$\theta_{z_i z_i} = (U_{z_i}^2 U_{z_i z_i} - 2U_{z_i} U_x U_{z_i x} + U_x^2 U_{xx})/U_x^3 < 0 \tag{A-4b}$$

These equations imply that the bid function is increasing and concave.

The bid function $\theta(\boldsymbol{z}; u, y)$ represents the maximum that the consumer is willing to pay to obtain the vector of characteristics $\boldsymbol{z}$ for a given level of utility u and income y, while the hedonic function $p(\boldsymbol{z})$ represents the minimum amount that the consumer has to pay for $\boldsymbol{z}$. Therefore, the utility of the consumer is maximized at the tangent of the bid and hedonic functions. That is,

$$\theta(\boldsymbol{z}^*; u^*, y) = p(\boldsymbol{z}^*) \tag{A-5a}$$

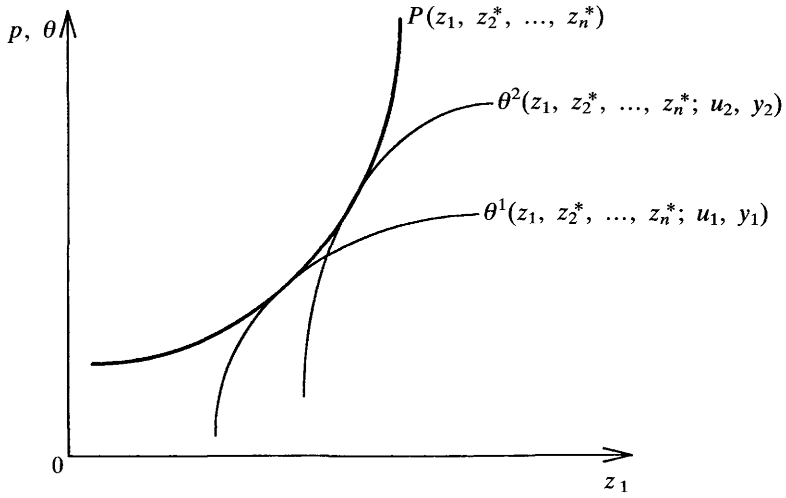
$$\theta_z(\boldsymbol{z}^*; u^*, y) = p_{\boldsymbol{z}}(\boldsymbol{z}^*) \tag{A-5b}$$

hold. The hedonic function can be viewed as an envelope function of the bid functions. Figure A-1 shows this situation for z_1.

Next, consider the profit maximization problem of the firm, which decides not only output M but also characteristics $\boldsymbol{z}$. Let $C(M, \boldsymbol{x})$ represent a cost function. The firm is assumed to be a price taker and to solve the following maximization problem:

$$\max_{\boldsymbol{z}, M} \pi = p(\boldsymbol{z})M - C(M, \boldsymbol{z}) \tag{A-6}$$

Figure A-1
Consumer Equilibrium



The first-order conditions are:

$$p_z(z) = C_z(M, z) \qquad \text{(A-7a)}$$

$$p(z) = C_M(M, z) \qquad \text{(A-7b)}$$

For an offer function $\phi(z, \pi)$, the following holds:

$$\pi = M\phi - C(M, z) \qquad \text{(A-8)}$$

Differentiating this equation with respect to z and π, we obtain:

$$\phi_z = C_z / M > 0 \qquad \text{(A-9a)}$$

$$\phi_x = 1/M > 0 \qquad \text{(A-9b)}$$

They imply that the offer function is increasing.

The offer function represents the minimum price that the firm is willing to offer for a product with characteristics of z, and the hedonic function represents the maximum price the firm can get in the market. Therefore, in equilibrium, the following conditions are satisfied:

$$p(z^*) = \phi(z^*, \pi^*) \qquad \text{(A-10a)}$$

$$p_z(z^*) = \phi_z(z^*, \pi^*) \qquad \text{(A-10b)}$$

Thus, the hedonic function can be viewed as an envelope function of the offer functions. Figure A-2 shows this situation for z_1.

Figure A-2
Producer Equilibrium

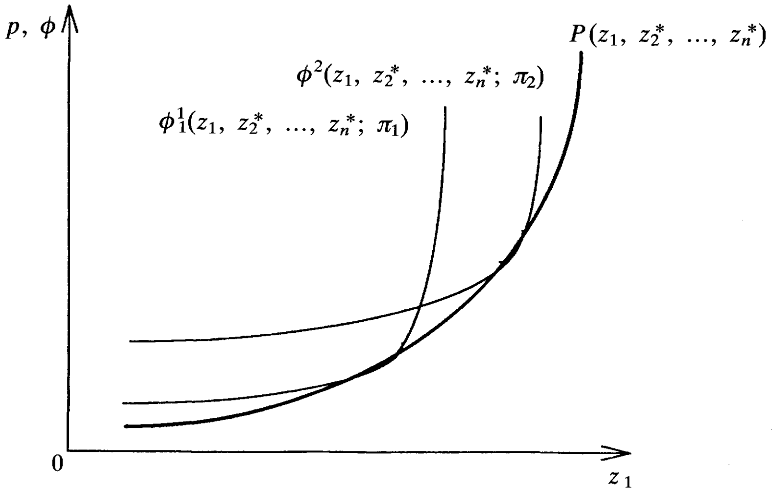
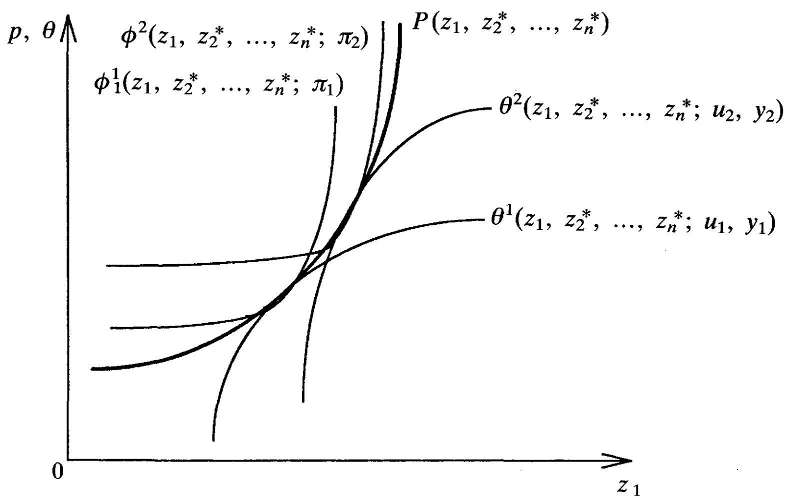


Figure A-3
Market Equilibrium



As a result, in equilibrium, buyers and sellers match perfectly, and the bid and offer functions are tangent to each other along the envelope curve, which represents the hedonic function. Figure A-3 shows this situation. Therefore, the hedonic function does not reflect any information about economic agents such as consumer preferences and production technology; instead it reflects the relationship between the observed market price and various characteristics of the product.[21] Nevertheless, if production technologies are identical, then the offer functions become the same for all firms and the hedonic function can identify the supply function. Similarly, if consumer preferences are identical, then the bid functions become unique and the hedonic function can identify the demand function.

Appendix B. Form of the Estimated Hedonic Function

As in many empirical studies on personal computers applying the hedonic approach in the United States, estimation of the hedonic function in this paper has assumed an ad hoc log-linear form. This appendix examines, from both theoretical and empirical perspectives, which functional form is the most appropriate to the hedonic function for personal computers, the Box-Cox transformation form, or such basic functional forms as the log-linear, semilog-linear, and simple linear form. Specifically, it compares those functional forms from the viewpoint of (i) estimation fit, (ii) theoretical consistency, (iii) simplicity of estimation, and (iv) ease of interpretation of estimation results. As to (iii), there is little doubt that log-linear, semilog-linear, and simple linear forms are superior because functional transformation is easy and OLS can be applied directly. As for (iv), the log-linear, and semilog-linear forms have some advantages in that a quality adjusted price index can be derived directly from estimated parameters of the annual dummies.[22] Therefore, in the following, (i) and (ii) above will be examined for those general functional forms.

Let us compare the fitness of the estimation results for various functional forms. Normally, the coefficient of determination provides the basic information about the degree of regression fitness, but it would not be appropriate for present purposes because the dependent variable is functionally transformed so that its variance will also be affected by the functional transformation. Consequently, we apply the Box-Cox test to compare regression fitness for different functional forms.[23] This is conducted in two steps: first, both the dependent and independent variables (excluding the dummy vari-

[21]The conclusion that the hedonic function simply reflects the relationship between the observed market price and characteristics implies that there is no *a priori* theoretical restrictions on its functional form.

[22]Estimated parameters of the annual dummies in log-linear, and semilog-linear forms can be interpreted as the log values of a quality adjusted price index. For the construction of a quality adjusted price index from the estimated results of the hedonic function, see Appendix C.

[23]For the Box-Cox test, see Chapter 11 of Greene (1993).

ables) are transformed according to the following Box-Cox transformation formula,[24] and then the Box-Cox parameters q and l are estimated by the maximum likelihood method.[25]

$$P_{it}^{(\theta)} = \alpha + \sum_{j=1}^{l} \beta_j x_{ijt}^{(\lambda)} + \sum_{j=l+1}^{n} \beta_j x_{ijt} + \sum_{k=1}^{T} \delta_k d_{ikt} + u_{it} \qquad \text{(A-11)}$$

where

$$P_{it}^{(\theta)} = \begin{cases} \dfrac{p_{it}^{\theta} - 1}{\theta} & \theta \neq 0 \\ \ln p_{it} & \theta = 0 \end{cases}$$

$$x_{ijt}^{(\lambda)} = \begin{cases} \dfrac{x_{ijt}^{\lambda} - 1}{\lambda} & \lambda \neq 0 \\ \ln x_{ijt} & \lambda = 0 \end{cases}$$

Here the characteristic variables x_{ijt} from l+1 to n are dummy variables and therefore are excluded from the Box-Cox transformation.

Table A-1 shows the log likelihood of the estimation results concerning the four different functional forms: the Box-Cox transformation form, the log-linear form, the semilog-linear form, and the simple linear form. According to the table, the Box-Cox transformation form has the highest log likelihood, followed by the log-linear, semilog-linear, and simple linear form in that order. The χ^2 test for the null hypothesis that the Box-Cox transformation parameters take a log-linear form ($\theta = \lambda = 0$) produces a test

Table A-1
Log Likelihood

	Box-Cox	Log Linear	Semilog Linear	Linear
λ	−0.1957	0	0	1
θ	−0.1571	0	1	1
Log Likelihood	−3,326.71	−3,235.33	−3,304.78	−3,592.96
Sum of Squared Residuals	4.0824	26.1014	33.3190	10,170,910

Note: The χ^2 test for the null hypothesis that the Box-Cox transformation parameters take a log-linear form($\theta = \lambda = 0$) : $\chi^2 = 17.2346 > 5.9915$

[24]The Box-Cox transformation is continuous at θ=λ=0 because l'Hospital's theorem implies that

$$\lim_{\lambda \to 0} \frac{x^{\lambda}-1}{\lambda} = \lim_{\lambda \to 0} \frac{d(x^{\lambda}-1)/d\lambda}{1} = \lim_{\lambda \to 0} x^{\lambda} \times \ln x = \ln x$$

[25]Amemiya (1985) pointed out that the Box-Cox transformation causes residuals to have a non-normal distribution because of the following restrictions on the transformed variable $z(\lambda)$:

value of 17.2346, which may be compared to the 5% critical value of 5.9915. Thus, the statistical results do not provide support for the log-linear form.

Next, to examine theoretical consistency, let us check the parameter signs of the Box-Cox transformation, and the log-linear form. Table A-2 shows the estimation results. The parameter signs are the same for all estimation coefficients between two forms. All the parameters for performance characteristics — clock frequency, memory size, hard disk capacity, monitor density, and number of expansion slots — show expected positive sign, and are statistically significant. The parameters for dummy variables also display the expected signs in general.

To sum up the above results, although the Box-Cox transformation form seems to have a better fit, it does not have enough advantages over the other forms to be used for estimation because of its technical complexity for estimating and interpreting results.

Appendix C. Methods to Calculate a Hedonic Price Indexes

This appendix discusses a method to calculate a quality adjusted price index from the estimation results of a hedonic function. Let us term a quality adjusted price index calculated from the estimation results of a hedonic function a "hedonic price index." The hedonic function used below to calculate the price index is the same function used in the text and takes the following form:

$$\ln P_{it} = \alpha + \sum_{j=1}^{n} \beta_j \ln x_{ijt} + \sum_{k=1}^{T} \delta_k d_{ikt} + u_{it} \qquad \text{(A-12)}$$

where x_{ijt} is the j-th characteristic of good i at period t, d_{ikt} a time dummy for period k, and u_{it} an error term.

The actual calculation method differs depending on whether or not it includes an annual dummy in the estimated hedonic function. When an annual dummy is included, the exponentially transformed value of the estimated parameter for the annual dummy becomes the quality adjusted price index for the full sample and 2-year sample estimations. Let x_j^* stand for the size of the j-th characteristic in the base year (t=0). Substituting this into equation (A-12), then annual dummies at t=0 (base period) all become 0, and for t=s (comparison period) the following holds:

$$z(\lambda) \geqq -1/\lambda \quad (\text{if } \lambda > 0)$$
$$\leqq -1/\lambda \quad (\text{if } \lambda < 0)$$

This makes the maximum likelihood estimators biased. Although Amemiya (1985) suggests the 2-stage nonlinear least square method is used for estimation, it is not frequently used because of its technical complexity. Because the methodology of the Box-Cox test is not the main subject of this paper and is used as a simple test to check the validity of functional forms in any case, this paper uses a simple maximum likelihood method for estimation. It is important, however, to keep in mind that the estimation may be biased as a result.

TableA-2
Comparison of Estimated Parameters for Box-Cox Transformation Form and Log-Linear Form

		Box-Cox		Log Linear	
Constant		1.9475	(0.660 *)	3.2022	(0.697 *)
Clock Frequency		0.2639	(0.117**)	0.3210	(0.133 *)
Memory		0.0290	(0.010 *)	0.0654	(0.024 *)
Hard Disk		0.0369	(0.012 *)	0.0567	(0.019 *)
Expansion Slot		0.1086	(0.031 *)	0.2436	(0.070 *)
Screen Density		0.3547	(0.252)	0.2693	(0.168)
Type	Laptop	0.0870	(0.029 *)	0.2272	(0.075 *)
	Notebook	0.0343	(0.021)	0.1048	(0.055**)
Monitor	Monochrome CRT	−0.0927	(0.038 *)	−0.2587	(0.100 *)
	Plasma LCD	0.1185	(0.053**)	0.3165	(0.137**)
	STN Color LCD	0.1576	(0.046 *)	0.3994	(0.118 *)
	TFT Color LCD	0.2217	(0.058 *)	0.5608	(0.147 *)
CPU	8 bits	−0.0801	(0.053)	−0.2699	(0.133**)
	16 bits	−0.0682	(0.023 *)	−0.1982	(0.064 *)
	Pentium	0.0985	(0.043**)	0.2137	(0.104**)
	Power PC	−0.0192	(0.040)	−0.0911	(0.104)
FD Drive (more than 2)		0.0185	(0.014)	0.0460	(0.036)
CD-ROM		−0.0147	(0.017)	−0.0419	(0.045)
Sound Function		−0.0176	(0.032)	−0.0450	(0.082)
Windows Preinstalled		−0.0328	(0.018**)	−0.0926	(0.048**)
Large Monitor		0.1554	(0.049 *)	0.4583	(0.142 *)
Year	1991	−0.0812	(0.024 *)	−0.1882	(0.058 *)
	1992	−0.1490	(0.040 *)	−0.3650	(0.099 *)
	1993	−0.2651	(0.069 *)	−0.6697	(0.176 *)
	1994	−0.3684	(0.094 *)	−0.9259	(0.237 *)
Maker	Acer	−0.2766	(0.096 *)	−0.7733	(0.258 *)
	Apple	0.0894	(0.030 *)	0.2484	(0.082 *)
	Compaq	−0.1108	(0.034 *)	−0.2685	(0.085 *)
	DEC	−0.1861	(0.080 *)	−0.5108	(0.210 *)
	Dell	−0.1609	(0.048 *)	−0.4376	(0.130 *)
	Epson	−0.0666	(0.021 *)	−0.1733	(0.054 *)
	Fujitsu	−0.0547	(0.026**)	−0.1495	(0.066**)
	IBM	−0.0927	(0.030 *)	−0.2233	(0.075 *)
	Packard Bell	−0.0641	(0.022 *)	−0.1424	(0.052 *)
	Toshiba	−0.2103	(0.067 *)	−0.5272	(0.169 *)

Note: Standard errors are in ( ); * and ** indicate statistical significance at 1 and 5% level; the standard errors may differ from the figures in the text because they do not make adjustments for the effects of heteroscedasticity.

$$d_{ist} = \begin{cases} 1\ (t=s) \\ 0\ (t \neq s) \end{cases}$$

Therefore, the estimated quality adjusted prices are given by:

$$\ln \hat{p}_0 = \hat{\alpha} + \sum_{j=1}^{n} \hat{\beta} \ln x_j^* \tag{A-13a}$$

$$\ln \hat{p}_s = \hat{\alpha} + \sum_{j=1}^{n} \hat{\beta} \ln x_j^* + \hat{\delta}_s \tag{A-13b}$$

where $\hat{}$ indicates that it is an estimated value.

Taking the difference between equations (A-13a) and (A-13b) gives:

$$\ln \hat{p}_s - \ln 76\hat{\mathrm{p}}_0 = \delta_s \tag{A-14}$$

which implies that the parameter (δ_s) for the annual dummy is the logarithm of a quality adjusted price index in period s relative to period 0. Therefore, the hedonic price index I_{0s} in period s relative to base period 0 (base period = 100) is obtained as:

$$I_{0s} = \exp(\delta_s) \tag{A-15}$$

Next, let us consider the 1-year estimation which does not include an annual dummy.[26] Taking the exponential of the value for the size of characteristic x_j^*, we can obtain the estimated quality adjusted price index as follows:

$$\hat{p}_0 = \exp(\alpha_0 = \sum_{j=1}^{n} \beta_{j0} x_j^*) \tag{A-16a}$$

$$\hat{p}_s = \exp(\alpha_s = \sum_{j=1}^{n} \beta_{js} x_j^*) \tag{A-16b}$$

Therefore the hedonic price index I_{0s} *for period s* relative to *t* he base period 0 is given by:

$$I_{0k} = \hat{p}_k / \hat{p}_0 \times 100 \tag{A-17}$$

[26]To calculate a quality adjusted price index without using an annual dummy, there are several other possible methods than evaluating estimated parameters by the average characteristics in the base year. For example, there is the "composite price index", which uses observed market prices for goods found in both base and comparison years, and estimated prices based on the hedonic function for goods found only in the base year (in aggregate with market share as weights). Another method is "characteristic price index", which evaluate estimated shadow with amount of characteristics of each good (in aggregate with market share as weights). For details on these methods, see Triplett (1988) and Cole, *et al.* (1986).

Appendix D. Basic Structure of a Personal Computer

A personal computer is a computer designed for an individual use. The basic structural elements are a computer body, called "hardware," and a program called, "software." This appendix explains the basic functions of these elements to better understand the text.

Figure A-4 describes the basic hardware structure of a personal computer. To understand the roles of the various elements, consider the example of running a word processing program. To write a paper using a personal computer, the first thing to do is to retrieve the word processing program from an auxiliary storage device (a floppy disk or a hard disk) to the main memory. The next step is to input words and edit instructions (*e.g.*, add, delete, or move a word) through the input device such as a keyboard, which are then processed by the CPU (central processing unit). Traditionally a keyboard has been used as the input device, but recently a "mouse" is used in new OS (operating system) called "Windows." The processing results are then temporarily stored in the main memory and at the same time are shown on the display. Once a paper is completed, it is saved as a file on the auxiliary storage devices and can be printed out by a printer. The saved file can be retrieved by specifying its file name from the auxiliary storage device to the main memory and can be edited. A more recent personal computer uses an extension board with circuits for additional sound and graphic capabilities, which can be connected to its "extension slots."

Figure A-4
Basic Hardware Structure of a Personal Computer

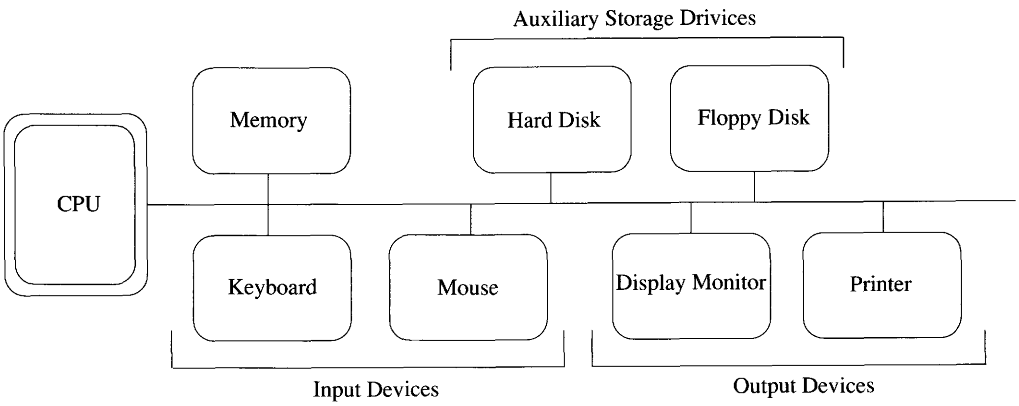
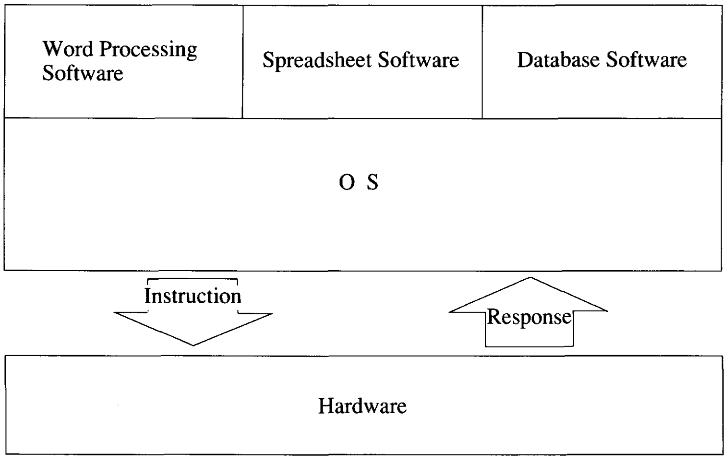


Figure A-5
The Relationship between AP-OS and Hardware



As for software, there are two types: basic software used for the operating system (OS) and application programs (AP). The AP is a computer program that can be used to accomplish a certain task like a word processing program discussed above. The user often runs multiple application programs on the same hardware. For example, the user may want to make charts and tables with a spread sheet program, and then place it in a text created by a word processing program. Here arises a need to save the charts and tables or the text as a file on a hard disk or a floppy disk. But it does not make any difference from a viewpoint of hardware whether the saving instruction comes from either software.

The OS resides between the hardware and the AP, and plays the role of controlling and coordinating their functions. The OS makes it possible to run multiple APs on the same hardware (Figure A-5). Although the DOS dominated the market as the main OS, the Windows has been gaining popularity with the users because of its superior ease-of-use and graphical user interfaces.

Shigenori Shiratsuka: Research Division I, Institute for Monetary and Economic Studies, Bank of Japan

Supplementary Table
Major Researches Using the Hedonic Approach

[U.S.A.]

Goods	Author(s)	Data sources	Dependent variables	Explanatory variables
Automobiles	Ohta, and Griliches. (1976)	NADA, *Official Used Car Guide.*	New car (List price), used car price	1. Weight 2. Length 3. Horse power 4. Hard top dummy 5. V8 dummy 6. Dummies for manufacturers 7. Year dummy
Capital goods	Ohta (1975)	Cowing (1969)	Boiler	1. Boiler rating 2. Boiler pressure 3. Boiler efficiency 4. Number of boilers installed 5. Dummy for type of construction 6. Dummy for primary fuel 7. Technical progress
			Turbogenerator	1. Capacity 2. Efficiency 3. Number of turbogenerators installed 4. Maintenance labor 5. Dummy for type of construction 6. Dummy for primary fuel 7. Technical progress
Electrical appliances	Gordon (1990)	*Sears catalog*, *Consumer Reports*, 1948-1983	Refrigerator	1. Capacity (Total, and freezer) 2. Number of doors 3. Dummy for refrigerator defrost 4. Dummy for icemaker 5. Dummy for cold water dispenser 6. Year dummy, etc.

Goods	Author(s)	Data sources	Dependent variables	Explanatory variables
Electrical Appliances (continued)			Air conditioner	1. Capacity (Horsepower or BTU) 2. Efficiency (watts or volts) 3. Year dummy, etc.
			Dishwasher	1. Capacity 2. Dummy for automatic drain 3. Dummy for automatic timer 4. Year dummy, etc.
Personal computers	Berndet, and Griliches (1993)	*Byte*, *PC Magazine*, *PC World*, *New York Times*, 1982-88	List prices, and discount prices	1. Memory size 2. Clock speed 3. Hard disk capacity 4. Number of floppy disk drives 5. Number of slots available for expansion board 6. Vintage dummy 7. Dummies for of processor chip type 8. Dummy for color monitor 9. Dummy for portable or convertible 10. Dummy for extra hardware included 11. Dummy for discounted price 12. Dummies for manufacturers 13. Year dummy
	Berndt, Griliches, and Rappaport. (1993)	*Datapro*, 1989-92	List prices	1. Memory size (installed, and maximum) 2. Clock speed 3. Hard disk capacity 4. Size 5. Weight 6. Dummies for type of processor chip 7. Dummy for portable or convertible 8. Dummy for more than two floppy disk drives 9. Dummy for no hard disk drive 10. Age dummy 11. Dummy for manufacturers 12. Year dummy

Goods	Author(s)	Data sources	Dependent variables	Explanatory variables
	Nelson, Tanguay, and Patterson (1994)	*PC Week*, *PC Magazine*, *PC Today*, *Tech PC Journal*, 1984-91	List prices	1. Clock speed 2. Memory size 3. Number of floppy disk drives 4. Hard disk capacity 5. Number of ports 6. Number of slots available for expansion board 7. Dummy for color monitor 8. Dummy for DOS installed 9. Dummy for EISA bus 10. Dummy for utility soft installed 11. Dummy for major manufacturers 12. Year dummy
Spreadsheets	Gandal (1994)	*Datapro*, 1986-92	List prices	1. Minimum of the maximum number of rows and columns 2. Dummy for products by Lotus 3. Dummy for basic graphic capabilities 4. Maximum number of windows on screen simultaneously 5. Dummy for compatibility with Lotus 6. Dummy for capability of linkage with external databases 7. Dummy for capability of uses through LAN 8. Dummy for linking value in several worksheets 9. Dummy for capability of programming-like macros 10. Dummy fpr capability of macros in learn mode 11. Dummy for capability of embedding graphs and using multiple fonts 12. Dummy for data sorting

Goods	Author(s)	Data sources	Dependent variables	Explanatory variables
Main frame computers	Gordon (1989)	*Computerworld*, 1951-84	List prices	1. Memory size 2. Machine cycle time 3. MIPS 4. Number of channels (minimum, and maximum) 5. Cache buffer size 6. Dummy for IBM products 7. Year dummy, etc.
	Dullberger (1989)	*Computerworld*, *Datamation*, 1972-84	List prices	1. MIPS 2. Memory size 3. Year dummy 4. Dummy for technological level
Apparel	Liegey (1993)	BLS data	Women's coats and jackets	1. Dummies for types (raincoat, all-weather, *etc.*) 2. Dummy for closure 3. Dummy for design (parka, trenchcoat, etc.) 4. Dummies for fiber (cotton, wool, etc.) 5. Dummy for lining
			Women's suits	1. Dummies for fiber (silk, wool, cotton, *etc.*) 2. Dummy for brand 3. Dummy for composition 4. Dummy for lining

【Japan】

Goods	Author(s)	Data sources	Dependent variables	Explanatory variables
Automobiles	Ohta (1978)	Oato Gaido, Ltd., *Red Book*	List prices in Tokyo	1. Length 2. Weight 3. Horsepower 4. Dummy for V8 engine 5. Dummy for hardtop model 6. Dummy for automatic transmission 7. Dummy for break type 8. Dummy for two doors 9. Dummies for automobile size 10. Dummy for manufacturers
Housing prices	Ito, and Hirono (1992)	*Shukan Jutaku Joho* (Housing Information Weekly)	Housing for rent and sale in Tokyo	1. Commuting time 2. Floor space 3. Age of the building 4. Dummy for 1st floor 5. Dummy for parking space available 6. Dummy for facing southeast 7. Dummy for facing south 8. Dummy for reinforced concrete structure
Land prices and rents	Suzaki, and Ohta (1994)	*Chika Koji* (Publication of Land Prices), *Shukan Jutaku Joho* (Housing Information Weekly)	Land prices, and rents per square meter in Kanagawa Prefecture	1. Commuting time to Tokyo Station 2. Commuting time to Shinjuku Station 3. Distance to the nearest station 4. Size 5. Dummy for availability of city gas 6. Dummies for railroads 7. Rank of average income
Hotel accommodation	Sawa, *et al.* (1989)	N.A.	Hotel accommodation for single room	1. Floor space 2. Number of credit cards available 3. Distance from the nearest station 4. Number of banquest halls 5. Restaurant space 6. Dummy for pool 7. Dummy for location (in Tokyo, or not)

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