Chapter 4

The Measurement of Quality Change: Constructing an Hedonic Price Index for Computers Using Multiple Regression Methods

"If a poll were taken of professional economists and statisticians, in all probability they would designate (and by a wide margin) the failure of the price indexes to take full account of quality changes as the most important defect in these indexes."

NATIONAL BUREAU OF ECONOMIC RESEARCH (1961, p. 35)

"My own point of view is that what the hedonic approach tries to do is estimate aspects of the budget constraint facing consumers, allowing thereby the estimation of 'missing' prices when quality changes."

ZVI GRILICHES (1988, p. 120)

". . . if the automobile and airplane businesses had developed like the computer business, a Rolls Royce would cost $2.75 and run for 3 million miles on one gallon of gas. And a Boeing 767 would cost just $500 and circle the globe in 20 minutes on five gallons of gas."

TOM FORESTER (1985, p. i)[1]

In this chapter we develop an understanding of how price indexes are constructed and interpreted, how quality and price are related, and how multiple regression analysis can be used to account for the effects of quality change. We focus attention on the interpretation of estimated coefficients in a multiple regression, including the dummy variable parameters.

Price indexes play a very important role in today's economies. For example, contracts between employers and employees often contain specific cost-of-living provisions for the automatic adjustment of wages or salaries due to changes in the Consumer Price Index (CPI). Similarly, government payments to senior citizens and other recipients of Social Security depend explicitly on changes over time in the CPI. Many long-term contracts between sellers and buyers include detailed provisions specifying how future transactions are to be affected by inflation, depending on changes in some particular price index. Policymakers, businesspeople, and analysts often want to know how measures such as sales, output, and costs should be deflated by a price index in order to obtain "real" quantity measures that adjust for the effects of inflation.

Because price indexes are so pervasive in today's economies, it is important that they be constructed with as much reliability and accuracy as is practically possible. Much has been written concerning the large number of important conceptual and statistical sampling issues encountered in constructing and interpreting both individual and aggregate price indexes.[2]

One very important issue concerns how price indexes should be adjusted to account properly for quality change. For products such as stylized raw materials, the physical specifications and characteristics typically remain unchanged over long periods of time; and for such products, quality change usually does not present a problem. However, for some products whose specifications and characteristics evolve rapidly over time, accounting properly for quality change becomes a very significant issue. In this chapter we will focus on one aspect of this problem and examine how regression methods can be used to construct quality-adjusted price indexes for individual products. In particular, we will construct an hedonic price index for computer-related products using multiple regression procedures.

The chapter proceeds as follows. In Section 4.1 we briefly summarize traditional procedures used in constructing price indexes that attempt to account for quality change. In Section 4.2 we examine the relationship between price and quality for a product at a given point in time. We show how this price-quality relationship can be analyzed by using regression analysis in which transaction prices are regressed on a number of explanatory variables, each measuring an important quality characteristic of the product. Then in Section 4.3 we extend the price-quality analysis into the intertemporal domain by showing how multivariate regression analysis can be used to measure the extent to which prices have changed over time, adjusting for quality by holding its level fixed. This procedure involves considerable use of dichotomous independent variables, more often simply called dummy variables.

In Section 4.4 we apply this general framework of hedonic price analysis to the specific problem of constructing a price index for computers. Computers are a particularly interesting application, since quality change in this industry has been very rapid and pervasive. Here we survey and review the empirical literature to date, including the recent innovations adopted by the U.S. Bureau of Economic Analysis. In Section 4.5 we discuss a number of econometric issues: the use of weighted least squares to adjust for heteroskedasticity, the choice of functional form, and the conditions under which parameters can be directly interpreted as estimates of the marginal costs or marginal consumer valuations of changes in the quality characteristics.

Finally, the exercises presented in this chapter involve you in the replication and extension of classic results reported in the empirical literature to date and are based on three very interesting data sets. The first is that gathered and employed by Frederick V. Waugh [1928] in his pioneering study of the effects of quality on vegetable prices. The second data set was constructed by Gregory C. Chow [1967] in his seminal study of demand for computers over the 1955–1965 era, and the third is a portion of one involving computers and computer peripheral products constructed by IBM in its recent study in conjunction with the U.S. Bureau of Economic Analysis.[3] The econometric procedures that you employ in these exercises include multiple regression analysis, the interpretation of R^2 and multiple correlation, dummy variables, hypothesis testing, tests for parameter stability, weighted least squares and tests for homoskedasticity, and Box-Cox estimation.

4.1 TRADITIONAL PROCEDURES FOR INCORPORATING QUALITY CHANGES INTO PRICE INDEXES

The traditional procedure for controlling for the effects of quality change on price is commonly called the "matched model" method. In this procedure the only prices used in constructing the index are those for models or varieties that are unchanged in specification between two adjacent time periods. The idea underlying this method is that matching the models ensures that any differences between the prices collected for the two time periods solely reflect price change, rather than a change in what in fact was purchased. In the United States the Producer Price Indexes (PPI), used for deflating many components of producers' durable equipment, are constructed by using the matched model method.

Two problems can arise with the matched model method that may prevent it from properly accounting for quality change.[4] One error can arise when the price changes observed for matched models do not accurately represent the price movements taking place for all models. For example, if new models of some product are introduced that embody an improved technology, and if the price index is based only on information gained from following prices of the incumbent models until they disappear from the market, it is possible that a substantial portion of the overall price change would not be uncovered by using matched model methods.

A second error can occur when models that are in fact not identical are nevertheless matched. This can arise when information on some of the specifications and characteristics of the models is unavailable or is not taken into account, so that some models that appear to be matches are in fact different. Alternatively, in some cases the statistical agency may know that the two models are not truly identical but may conclude that if the differences are small, it is preferable to make the match rather than drop the price information from the index entirely.

Dealing with each of these two possible errors involves facing a tradeoff. The stricter the criteria for accepting two models as a match, the greater the number of models that will be excluded from the price index. This implies that, with the matched model method, the more one guards against the second possible error (matching not completely identical models), the more likely it is that the index will contain the first error (inferring incorrect information for unmatched models based on that observed for matched models).

Regression analysis can help considerably in reducing the severity of this tradeoff. After years of encouragement from a number of distinguished economists, in 1986 the U.S. Bureau of Economic Analysis published and incorporated into its official statistics the results of a study on computer prices in which the matched model method was augmented by a particular type of regression analysis known as *hedonic price analysis*.[5] In one type of hedonic price analysis the matched model method is employed whenever the appropriate data are available, and then hedonic regression methods are used to impute missing prices for newly introduced or just discontinued models, thereby accounting more fully for the price changes associated with turnover of models available in the market. In another type of hedonic price analysis the price index is estimated directly from a regression equation.[6] In either case, hedonic price analysis forms the basis of the measurement of quality change.

4.2 ANALYZING THE PRICE-QUALITY RELATIONSHIP AT A GIVEN POINT IN TIME

In this section we discuss the relationship between price and quality at a given point in time by reviewing some of the early empirical literature. In terms of today's standards for econometric practice, this pioneering literature leaves much to be desired. Interestingly, while much recent hedonic price research has focused on quality-adjusted prices for computers, the first hedonic price equations were estimated without the benefit of any computers whatsoever. Therefore in assessing this early literature, it is worth bearing in mind that today's computational hardware and software tools were simply not available in the 1920s. As we shall see, however, an important contribution of the early studies consisted of establishing the notion that price variations reflect quality differentials.

The early empirical research on measuring the effects of quality on price was for the most part not concerned with implications for price indexes, but had other purposes in mind. Apparently, the first empirical study relating price and quality was that of Frederick Waugh, an agricultural economist who in 1927 wrote a paper entitled "Quality Factors Influencing Vegetable Prices."[7] The goal of Waugh's research was, using statistical analysis, "to discover the important quality factors which cause high or low prices" [1928, p. 186]. In his paper, Waugh reported results, based on multiple correlation analysis, in which he considered the effects of physical characteristics—size, shape, color, maturity, uniformity, and other factors—on the prices of asparagus, tomatoes, and hothouse cucumbers as recorded in daily sales transactions at the Faneuil Hall wholesale market in downtown Boston, Massachusetts.

Waugh had rather practical motivations for his research. Noting that profit-maximizing farmers can to some extent adjust both the quantity and quality of commodities produced to meet market demand conditions, Waugh emphasized the usefulness of his research by stating that [1928, p. 187]

> If it can be demonstrated that there is a premium for certain qualities and types of products, and if that premium is more than large enough to pay the increased cost of growing a superior product, the individual can and will adapt his production and marketing policies to market demand.

To eliminate the effects of seasonal and day-to-day changes in prices, Waugh used as a left-hand or dependent variable in his regression equations the ratio of the actual price recorded for a wholesale market lot transaction of a particular commodity (denoted P_{in}) to the average market quotation for that commodity that day (PM_i). Call this relative price of the nth lot transaction for the ith commodity p_{in}, and note that it is defined as

$$p_{in} = P_{in}/PM_i \tag{4.1}$$

Waugh regressed p_{in} on the physical characteristics of vegetables that he believed were related to their actual or perceived quality variations. Although he reported separate results for asparagus, tomatoes, and hothouse cucumbers, here we confine our attention to his analysis of asparagus.

Waugh inspected 200 individual lots of asparagus in Boston over the time period of May 6 to July 2, 1927. Apparently, a great deal of quality variation existed among lots of asparagus, since even on the single day of July 2, prices per bushel box varied from a low of \$4.50 to a high of \$12.00. Waugh characterized qualitative differences among lots as follows:

> One lot was extra fancy. It was green from tips to butts. The stalks were large, straight and of uniform size. The bunches were compact. The other lot was classified as "junk." It was white. The stalks were small, crooked, and uneven in size. The bunches were loose. The butts were jagged and uneven.[8]

To quantify the effects of quality variables on relative prices, Waugh chose three measures that he believed were related to perceived quality. The first was the number of inches of green color on the asparagus; name this variable GREEN. The second variable was designed to capture the average size of stalks and was measured by the number of stalks in the bunches; call this variable NOSTALKS. Since the standard size of bunches was about 18 ounces, the number of stalks in a bunch increased as their size or diameter became smaller. Finally, to capture the effect of uniformity, a record was kept of the actual diameter of each stalk, and then the variation in size was measured by using the quartile coefficient of dispersion; denote this variable DISPERSE.

Waugh is not completely clear on precisely how he performed his regression analysis, but it appears to have had some problems, at least by today's standards. Waugh's aim was to estimate parameters in the multiple regression equation

$$\begin{aligned} p_n = \beta_0 + \beta_1 \cdot \text{GREEN}_n + \beta_2 \cdot \text{NOSTALKS}_n \\ + \beta_3 \cdot \text{DISPERSE}_n + u_n \end{aligned} \tag{4.2}$$

for $n = 1, \ldots, 200$, where the least squares estimates of β_1, β_2, or β_3 could be interpreted as representing the partial effect of a change in one quality characteristic on price, all other quality characteristics being held fixed. Although Waugh assumed that u_n was a random disturbance term with mean zero, he did not give it a specific interpretation.

Using what he called the method of multiple correlation analysis, Waugh [1929, p. 144] reports the following estimates of the regression equation parameters in Eq. (4.2), where e_n is the equation residual:

$$\begin{aligned} p_n = \beta_0 + 0.13826 \cdot \text{GREEN}_n - 1.53394 \cdot \text{NOSTALKS}_n \\ - 0.27553 \cdot \text{DISPERSE}_n + e_n \end{aligned} \tag{4.3}$$

No estimate is provided for the intercept term β_0, nor are values given for the estimated standard errors and t-statistics.[9]

Waugh commented on his empirical findings as follows. First, he reported that green color is by far the most important quality factor influencing asparagus prices in Boston: "Boston wants green asparagus" [1928, p. 188]. Waugh noted that the predicted price per dozen bunches of asparagus that were green throughout a length of six inches from the tip was 38.5 cents more than asparagus having only five inches of green color. The coefficient of determination for the GREEN variable was 0.40837, which led Waugh to state that [1928, p. 188] "the influence of this one factor explained 41 percent of the variation in prices found in the 200 inspections."

With respect to size of the asparagus, Waugh [1929, p. 144] commented that on the basis of his estimated regression coefficient, for each additional stalk in the bunch the price was predicted to decrease by about 4.6 cents per dozen bunches. In terms of explanatory power, Waugh reported that the coefficient of determination for the NOSTALKS variable was 0.14554. Finally, concerning uniformity, Waugh's analysis revealed that the premium paid for uniformity in size was small; further, the coefficient of determination for the DISPERSE variable was also rather small, equaling only 0.02133.

The size of the relative coefficients of determination for these three separate regressors led Waugh to conclude that the uniformity variable

> was about one-seventh as important as size of stalk and one-twentieth as important as green color in its effect on prices. The three together explained 58 percent of the price variation. The coefficient of multiple correlation between these three quality factors and prices received was 0.76.[10]

To interpret Waugh's regression results, we focus on two questions. First, were his estimates of the multiple regression coefficients correctly computed? Apparently not. This issue will be dealt with in Exercises 1 and 2 at the end of this chapter. Second, did he measure goodness of fit properly? Here the answer is clearly no, at least by today's standards. Waugh relied heavily on the notion of the coefficient of determination in interpreting which variables were most important and how they contributed to explaining variation in prices.

In the multiple regression context it may be tempting to decompose the R^2 from an estimated equation into additive components, indicating what proportion of the variance in the dependent variable is distinctly attributable to variations in each of the right-hand variables.

This temptation should be resisted. The problem with such a decomposition is that in general it is impossible to compute unambiguously the individual contribution of each right-hand variable to the explanation of variations in the dependent variable. The only exception to this is when each of the right-hand variables is orthogonal to each of the other regressors.

Coefficients of determination attempt to measure contributions of variables, but since there is some ambiguity about the definition of coefficient of determination, it will be useful for us first to distinguish partial from separate coefficients of determination.

Consider first the *partial* coefficient of determination, which attempts to measure the marginal proportional contribution of a regressor to the explanation of variance in the dependent variable, *given all the other regressors.* The partial coefficient of determination for variable X_j is computed as the R^2 from a regression equation in which two sets of residuals are regressed against each other, one from a regression of Y on all X's except X_j and the other from a regression of X_j on all other X's.[11] The major problem with this measure is that the sum of the marginal contributions over the various right-hand variables does not in general equal the R^2 from the original multiple regression equation, in part because each of the partial coefficients of determinations is computed given a different set of other regressors.

An alternative measure used by some to attempt to measure the contribution of an individual regressor is called the *separate* coefficient of determination. Suppose we had a multiple regression equation of the form

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \cdots + \beta_K X_{Ki} + u_i \qquad i = 1, \ldots, n \tag{4.4}$$

and denote least squares estimates of the β's with b's. The separate coefficient of determination for the jth regressor is computed as

$$d^2_{Y \cdot X_j} = b_j \frac{\sum_{i=1}^{n} (X_{ij} - \overline{X}_j) \cdot (Y_i - \overline{Y})}{\sum_{i=1}^{n} (Y_i - \overline{Y})^2} \tag{4.5}$$

It may be tempting to sum the separate coefficients of determination over all the regressors and interpret the result as the total proportion of variation "explained" by the regressors, that is, to interpret this sum as equaling the conventional R^2 goodness-of-fit measure. Unfortunately, however, there is no clear relationship between the conventional R^2 measure from multiple regression equation analysis and the $\Sigma_{j=1}^{K} d^2_{Y \cdot X_j}$.

Which notion of the coefficient of determination did Waugh have in mind? We do know that the 58% total coefficient of determination figure reported by him equals the sum of the coefficient of determination values from the three separate regressors—0.58 = 0.41 + 0.15 + 0.02. Moreover, as we shall see in Exercise 2, Waugh apparently computed coefficients of determination using Eq. (4.5), that is, he computed separate coefficients of determination.

It is important to note that unless the regressors GREEN, NOSTALKS, and DISPERSE are pairwise uncorrelated (and this in fact was not the case), the 0.58 figure calculated as this sum is not equal to the traditional R^2 figure computed in today's typical regression programs.[12] Hence not only was it incorrect for Waugh to attribute the relative importance of contributions from the regressors GREEN, NOSTALKS, and DISPERSE as equaling 0.41, 0.15, and 0.02, respectively, but it was also incorrect for him to state, as was quoted above, "The three [regressors] together explained 58 percent of the price variation." An implication of this is that without being able to examine further the original data, it is not clear what statistical significance can be attributed to Waugh's empirical results. Fortunately, Waugh published his original data in appendices at the end of his 1929 book, and this will enable us to analyze them further in Exercises 1 and 2 at the end of this chapter.

By today's computational and statistical standards, therefore, Waugh's analysis was somewhat flawed. However, for our purposes it should be borne in mind that Waugh's particularly valuable and enduring insight was to see the possibility of using statistical methods for assessing the relationship between price and quality at a given point in time, having eliminated the effects of seasonal and day-to-day price variations by using relative prices. In the next section we extend Waugh's reasoning by examining how quality variations among varieties and over time can be dealt with simultaneously by using multiple regression analysis.

4.3 MEASURING PRICE-QUALITY RELATIONSHIPS OVER TIME

Although one often observes quality differentials among goods at a given point in time, quality changes also occur over time, owing in part to the forces of technological change. As we shall now see, regression analysis, particularly involving dummy variables, can help considerably in dealing with quality adjustment of price indexes over time. This type of regression analysis has become known as hedonic price analysis. A brief historical background on hedonic prices may be of particular interest here.

In the late 1930s in the United States, owing in part to the relatively large size of General Motors (GM) and the existence of substantial cyclical unemployment, public policy debates arose in Congress and elsewhere over whether GM should be required to vary prices of its automobile models in order to stabilize production volumes and employment levels. Some critics argued that GM had been using its monopoly power ruthlessly and that it could be employed more constructively. As evidence, they noted that over the 1925–1935 time period, the U.S. Bureau of Labor Statistics (BLS) official new car price index for the GM brands had increased 45%; moreover, the index of GM new car sales demonstrated considerable variability from year to year.

Stung by this criticism and alarmed at the prospect of such government intervention, in 1938 GM funded a study by Andrew T. Court of the Automobile Manufacturers' Association to assess the effects of auto price changes on the total volume of auto sales.[13]

One of the first issues that Court faced was the choice of the price variable to be used as an explanatory variable in the demand for automobile equation. Should it be average list price? If it were, it would not properly account for the quality improvements over the 1925–1935 time period in the increased horsepower, comfort, speed, and reliability of the GM models. Court could have used the BLS official new car price index, but at that time this price index was based simply on average list prices by brands, and no account was taken of changing specifications and quality improvements.[14] In particular, within a brand, no distinction was made between standard, fully equipped cars and special, stripped economy models that were offered without starter, battery, generator, and spare tire. This sole reliance on brand contrasted with the BLS procedures that were operative at that time for farm tractors and trucks, the official price indexes of which were computed by using matched model methods involving certain physical specifications. Apparently, the BLS believed that use of matched model methods for automobiles would have been inadequate because of the complexity of the problem.

Court devised an alternative procedure, which he called the hedonic pricing method. Invoking utilitarian philosophies that promoted hedonistic thinking—seeking the greatest happiness of the community as a whole—Court [1939, p. 107] defined hedonic price comparisons as "those which recognize the potential contribution of any commodity, a motor car in this instance, to the welfare and happiness of its purchasers and the community." Automobiles, he noted, produce a number of services that consumers enjoy. It would be desirable to measure directly the amount of happiness and increased welfare provided by automobile services, but such quantification would, of course, be impossible. However, it might be reasonable to relate the enjoyment consumers receive from automobiles to physical design and operating characteristics, such as power, speed, internal room, safety, and the like. Court then argued as follows:

> In the case of passenger cars, if the relative importance to the customer of horsepower, braking capacity, window area, seat width, tire size, etc., could be established, the data reflecting these characteristics could be combined into an index of usefulness and desirability. Prices per vehicle divided by this index of Hedonic content would yield valid comparisons in the face of changing specifications.[15]

Following a suggestion made to him by Sidney W. Wilcox, then the Chief Statistician of the U.S. Bureau of Labor Statistics, Court proceeded to measure the relative importance of automobile characteristics to customers by estimating parameters in a multiple regression equation, based on historical data, by model and by year, on list prices and measures of relevant automobile characteristic specifications.

As an example of Court's thinking, consider the case of various new automobile models introduced in three model years, say, 1925, 1926, and 1927. Suppose, as did Court, that three characteristics relate to automobile quality: the dry weight of the car in pounds (WT), the length of the wheelbase in inches (LH), and the advertised horsepower (HP). Denote the price of model i as P_i, and in addition to the intercept term, define two dummy variables, $D_{1926,i}$, a variable that takes on the value of 1 if model i is from the model year 1926 and zero otherwise, and $D_{1927,i}$, a variable that takes on the value of 1 if model i is from model year 1927 and zero otherwise.

Within this context, Court proposed estimating the following hedonic regression equation:

$$\ln P_i = \alpha_0 + \alpha_1 \cdot D_{1926,i} + \alpha_2 \cdot D_{1927,i} + \beta_1 \cdot \mathrm{WT}_i + \beta_2 \cdot \mathrm{LH}_i + \beta_3 \cdot \mathrm{HP}_i + u_i \tag{4.6}$$

where the α's and β's are unknown parameters to be estimated and u_i is assumed to be an identically and independently normally distributed disturbance term with mean zero and variance σ^2. Incidentally, the intercept term α_0 refers to the 1925 year, and so it is necessary to have only two dummy variables, $D_{1926,i}$ and $D_{1927,i}$, even though data from three years are being employed. Data necessary to estimate parameters in Eq. (4.6) consisted of a number of observations on different new car models sold in model years 1925, 1926, and 1927.

The importance of this hedonic regression equation to the construction of price indexes that account for quality change emerges from the interpretation of the regression coefficients, particularly α_1 and α_2. Suppose that two automobile models were introduced, alike in all quality respects except that one was introduced in model year 1925 and the other in model year 1926; denote their common weight, length, and horsepower as WT*, LH*, and HP*, respectively, and their distinct prices as P_{1925} and P_{1926}. Since quality-related characteristics are identical, any price change between the two years is a pure price change, unrelated to quality variations. The least squares predicted price for the model introduced in 1925 is

$$\ln \hat{P}_{1925} = \hat{\alpha}_0 + \hat{\beta}_1 \cdot \mathrm{WT}^* + \hat{\beta}_2 \cdot \mathrm{LH}^* + \hat{\beta}_3 \cdot \mathrm{HP}^* \tag{4.7}$$

while the predicted price for the model introduced in 1926 is

$$\ln \hat{P}_{1926} = \hat{\alpha}_0 + \hat{\alpha}_1 + \hat{\beta}_1 \cdot \mathrm{WT}^* + \hat{\beta}_2 \cdot \mathrm{LH}^* + \hat{\beta}_3 \cdot \mathrm{HP}^* \tag{4.8}$$

where the $\hat{\alpha}$'s and $\hat{\beta}$'s refer to least squares estimates of α and β (obtained, say, from a larger sample), and the $\hat{P}$ implies the predicted or fitted log-price.

Since in this example any price change between years 1925 and 1926 is a pure price change unrelated to quality variations, we can compute the pure price change simply by taking differences in the predicted prices of 1926 and 1925. Subtracting Eq. (4.7) from Eq. (4.8) yields

$$\ln \hat{P}_{1926} - \ln \hat{P}_{1925} = \hat{\alpha}_1 \tag{4.9}$$

Hence the estimate of α_1 represents the estimated change in the natural logarithm of the price index for new car models from 1925 to 1926, quality being held fixed.

If an identical model were also sold in 1927, similar reasoning would yield an interpretation of the estimate of α_2 as representing the estimated total change in the natural logarithm of the quality-adjusted price index for new car models over the two years from 1925 to 1927. The change in the natural logarithm of the estimated quality-adjusted price index for new cars over the single year from 1926 to 1927 would therefore be equal to the difference between the estimates of α_2 and α_1.

While the above interpretation of α_1 and α_2 is based on an example in which quality levels have been constrained to be identical in 1925 and 1926, this interpretation holds much more generally. Recall that in a multiple regression equation the least squares estimate of a parameter refers to a change in one right-hand variable, all others being held fixed. In this particular case we can therefore interpret the estimate of α_1 as reflecting the estimated change in ln P, due to the passage of time, holding all other variables—in this case, including all quality variables—constant. Thus in a very natural way the estimated coefficients on the time dummy variables represent changes in the natural logarithm of the price index for new cars, quality being held fixed.

Let us now arbitrarily normalize the level of the quality-adjusted new car price index to 1.00 in 1925. To create estimates of this price index for 1926 and 1927, we take appropriate antilogarithms, that is, we exponentiate as follows:[16]

$$\begin{aligned} &\text{Quality-adjusted price index for 1926:} \quad e^{\hat{\alpha}_1} \\ &\text{Quality-adjusted price index for 1927:} \quad e^{\hat{\alpha}_2} \end{aligned} \tag{4.10}$$

Incidentally, had Court specified a regression equation in which the dependent variable was P rather than ln P, then the quality-adjusted price indexes would have been computed as 1.00, $1 + \hat{\alpha}_1$, and $1 + \hat{\alpha}_2$ for 1925, 1926, and 1927, respectively. The reason Court chose the semilogarithmic equation specification over the linear one was grounded in goodness-of-fit criteria; on the basis of a preliminary analysis, Court reported that the semilogarithmic form was found to give "higher simple correlations."[17]

Within the context of Court's hedonic price equation it is possible to test statistically a number of interesting hypotheses. One hypothesis is of the form that "quality does not matter," that is, that price variations in no way reflect quality differences. Notice that if in Eq. (4.6) $\beta_1 = \beta_2 = \beta_3 = 0$, then variations in WT, LH, and HP would not be associated with changes in ln P. Hence the "quality does not matter" hypothesis could be implemented empirically by testing the joint null hypothesis that $\beta_1 = \beta_2 = \beta_3 = 0$ against the alternative hypothesis that $\beta_1 \neq 0$, $\beta_2 \neq 0$, or $\beta_3 \neq 0$.

In addition to this joint test involving three coefficients, one could of course also test that one particular quality characteristic is not significant. In the case of Eq. (4.6), for example, one could test the hypothesis that wheelbase length (LH) does not matter, simply by testing the null hypothesis that $\beta_2 = 0$ against the alternative hypothesis that $\beta_2 \neq 0$.

A different hypothesis is that all price variations from 1925 to 1927 correspond with quality variations and therefore that during this time span there has been no change in the quality-adjusted price index, that is, once adjusted for quality change, there has been no inflation. In the context of Eq. (4.6), such a null hypothesis is $\alpha_1 = \alpha_2 = 0$, while the alternative hypothesis is that $\alpha_1 \neq 0$ and $\alpha_2 \neq 0$. The null hypothesis that there has been no quality-adjusted price change between only two years, say, 1926 and 1927, could be implemented by testing $\alpha_2 - \alpha_1 = 0$ against the alternative $\alpha_2 - \alpha_1 \neq 0$.

Finally, suppose one wanted to measure how much quality change per automobile had in fact taken place over the 1925–1927 time interval. Recall that while prices per automobile had risen considerably over the 1925–1927 time period, according to Court, at least some of this price increase should be attributed to quality improvements. The quality levels embodied in 1927 models as compared to 1925 models could be computed in two different, but numerically equivalent, ways. This can be seen by subtracting estimates of $(\alpha_1 \cdot D_{1926,i} + \alpha_2 \cdot D_{1927,i})$ from both sides of the estimated version of Eq. (4.6) as follows:

$$\ln \hat{P}_i - \hat{\alpha}_1 \cdot D_{1926,i} - \hat{\alpha}_2 \cdot D_{1927,i} = \hat{\alpha}_0 + \hat{\beta}_1 \cdot \mathrm{WT}_i + \hat{\beta}_2 \cdot \mathrm{LH}_i + \hat{\beta}_3 \cdot \mathrm{HP}_i \quad (4.11)$$

To interpret this equation, let us suppose that two models were being compared, model $i = A$ from 1925 and model $i = B$ from 1927. Given the values of the characteristics of these two models and the estimated parameters, one could focus on and compute either side of Eq. (4.11). If one calculated the left-hand side, in essence the logarithm of the quality-adjusted price index (the logarithm of Eq. (4.10)) would be subtracted from the least squares fitted quality-unadjusted price in logarithms. This is equivalent to taking the logarithm of the *ratio* of the fitted quality-unadjusted price to the estimated quality-adjusted price. The difference between these two is the logarithm of the estimated quality difference between models A and B.

Alternatively, one could focus on the right-hand side of Eq. (4.11) and simply substitute into it the values of the WT, LH, and HP characteristics for models A and B along with the corresponding parameter estimates. The difference between the two model values would then be directly interpreted as the logarithm of their quality ratio.

Note that in either case the hedonic technique converts the "quality problem" into a quantity measure. Court's methodological contribution to the construction of quality-adjusted price indexes was therefore a most important and significant one. As we shall see in the next section, much recent work—including that on computers—has been based on the framework established by Court in 1939.

The curious reader might wonder what ultimately became of Court's hedonic price research. In terms of contributing to the public policy debate involving more cyclical pricing behavior by GM, Court's findings were dramatic and significant. While the BLS official new car price index rose 45% over the 1925–1935 time period, Court's proposed quality-adjusted new car price index *decreased* approximately 55%.[18] GM officials used these empirical findings along with other data in developing their argument that automobile manufacturers had already been reducing quality-adjusted prices and that any further price decreases designed to stabilize employment would likely lead the auto manufacturers to the "brink of insolvency," since the required break-even volume would be much larger than the price-induced increase in demand for new cars.[19]

In terms of generating new empirical research, however, it is somewhat surprising that Court's methodological contributions were not immediately influential. Indeed, for more than two decades the only subsequent research

ZVI GRILICHES

Father of Modern Hedonic Price Analysis

The ongoing professional interest in the use of regression analysis to adjust price indexes for quality change is due in large part to the work of Zvi Griliches, who in 1961 presented before hearings in the U.S. Congress a seminal analysis entitled "Hedonic Price Indexes for Automobiles: An Econometric Analysis of Quality Change." Griliches' research is widely recognized as having formed the basis of modern hedonic price analysis.

Zvi Griliches was born in Lithuania of Jewish parents in 1930. At age 11, Griliches was moved, along with his parents, into the German-occupied Kaunas Ghetto, where he remained until 1944, when he and his father were separated from his mother and were shipped to a working camp of the Dachau concentration system. Orphaned at the age of 14, Griliches was liberated by Patton's 3rd Army in May 1945 and arrived in Palestine via the "underground railroad" (actually a boat) in September 1947 after a seven-month internment in a British camp on Cyprus. He then spent several years in various kibbutzim, focusing much of his spare time on learning English and mathematics, teaching himself enough to pass an external high school equivalence examination in 1950.

After studying history for a year at the Hebrew University, Griliches applied to and was accepted by the University of California at Berkeley. Griliches chose agricultural economics as his major field of study because to leave Israel at that time, one had to be going to study something "essential." Griliches completed Berkeley's undergraduate degree requirements in two years, receiving a B.S. degree with highest honors in 1953 and an M.S. in 1954, and learned his first econometrics from George Kuznets (Simon's brother). He then transferred to the University of Chicago, where he studied additional econometrics with Roy Radner, Henri Theil, Trygve Haavelmo, and Carl Christ. His 1957 Ph.D. dissertation, "Hybrid Corn: An Exploration of the Economics of Technological Change" (published in *Econometrica*) earned him the best published research award from the American Farm Economic Association.

Although Griliches is widely recognized for his work on hedonic price analysis, his research has ranged widely, and today he is equally well known for major contributions to the analysis of productivity growth and technical change (see Chapter 9 of this book), estimating rates of return to education (Chapter 5), analyzing patent statistics, and the econometric specification and interpretation of distributed lags (Chapters 6, 7, and 8).

Zvi Griliches' initial academic appointment was at the University of Chicago. In 1969 he moved to Harvard University, where he now is the Paul M. Warburg Professor of Economics. He teaches graduate courses in applied econometrics and econometric methods and conducts two seminars, one in econometrics and the other in labor. He is a Fellow of the Econometric Society, served as its President in 1975, was coeditor of *Econometrica* for a decade, and is a recipient of the distinguished John Bates Clark Medal from the American Economic Association. He is also an elected Member of the National Academy of Sciences.

To Zvi Griliches, doing empirical econometrics involves one in a wonderful research venture that can involve numerous frustrations and surprisingly circuitous paths. In a 1977 *Econometrica* article he described this process, quoting from A. A. Milne's *The House at Pooh Corner* as follows:

> "How would it be," said Pooh slowly, "if, as soon as we're out of sight of this Pit, we try to find it again?"
>
> "What's the good of that?" said Rabbit.
>
> "Well," said Pooh, "we keep looking for Home and not finding it, so I thought that if we looked for this Pit, we'd be sure not to find it, which would be a Good Thing, because then we might find something that we weren't looking for, which might be just what we were looking for, really."
>
> "I don't see much sense in that," said Rabbit.
>
> "No," said Pooh humbly, "there isn't. But there was going to be when I began it. It's just that something happened to it on the way."

published on hedonic pricing was relatively obscure, consisting of several theoretical notes and empirical illustrations, including one by Richard Stone on computing a "price per unit of inebriation" for alcoholic beverages.[20]

Court's hedonic multiple regression approach to the construction of price indexes was finally revived in 1961 by Zvi Griliches.[21] Unlike Court's, Griliches' work immediately stimulated a substantial and very influential body of new research, both theoretical and empirical, that continues to this day.[22] Although Court's notion of hedonic prices focused on the demand side, the post-Griliches research typically envisages hedonic prices as the outcome of shifting supply and demand curves for characteristics. Further, as was noted in the introduction to this chapter, Griliches' revival of the hedonic method has now attained an official status; in 1986 the U.S. Bureau of Economic Analysis released official price indexes for computers based in part on the results of hedonic multiple regressions.[23]

4.4 APPLICATIONS OF THE HEDONIC METHOD TO PRICE INDEXES FOR COMPUTERS

Although Court's hedonic price framework has been applied in a host of empirical studies analyzing quality change in various goods and commodities, it is computers and automobiles that have received the greatest share of attention from applied econometricians. In this section we survey and review various applications of the hedonic price procedure to the estimation of quality-adjusted price indexes for computers. Computers provide a particularly interesting application, since quality improvement in the computer industry has been rapid and pervasive. Before we begin this survey, however, we first make some more general comments on the hedonic pricing procedure.

Implicit in the hedonic price framework is the assumption that the numerous models and varieties of a particular commodity can be viewed as consisting of various combinations, bundles, or composites of a smaller number of characteristics or basic attributes. In brief, the hedonic hypothesis is that heterogeneous goods are aggregations of characteristics. Moreover, implicit marginal prices for the characteristics can be calculated as derivatives of the hedonic price equation with respect to levels of the characteristics.

Once one views heterogeneous goods as aggregates of individual characteristics, it becomes clear that the relationship between the overall bundle price and the level or quantity of the various characteristics need not be constant over time, that is, implicit prices may change over time. Firms can be viewed as supplying various combinations of characteristics, and consumers can be envisaged as demanding them. When supply or demand curves for characteristics shift, the implicit price relationships between the overall price of the bundle and the individual characteristics might also change.

For example, recall the motivation of Waugh's research on quantifying the effects of consumers' valuations of vegetable quality on price. Suppose producers responded to a particularly perceived premium and increased the supply of, say, green asparagus. Would this change the size of the market premium for green asparagus? More generally,

> Will the premium paid for products of high quality tend to remain constant, or will it change with variations in the proportion of the different grades of qualities on the market?[24]

The answer to this question depends, of course, on the underlying supply and demand relationships for the characteristics. As we shall see later on, while in general it is difficult to recover consumers' utility functions and/or producers' cost functions from the hedonic regression equation, viewing observations of price-characteristic combinations as representing the outcomes of an underlying and potentially changing supply-demand framework suggests that in empirical implementations, particular care should be given to checking whether the parameters of hedonic price equations are stable over time.

In this context it is useful to note very briefly the major changes that have occurred since the 1950s in the computer industry.[25] It is traditional to characterize the commercial history of mainframe computers as consisting of three generations. By most accounts the first generation of computer history began with the earliest models sold commercially in the United States, beginning in 1953 and 1954, and ended in about 1959–1960, when models were introduced in which solid-state transistors replaced vacuum tubes. This second generation of computers reigned until about 1964 or 1965, when integrated circuit technology was introduced. The third-generation computers embodying the integrated circuit technology, exemplified by the IBM 360 series, displayed a considerably improved price-performance ratio relative to its predecessors.

In addition to these changes in computer hardware, the marketing of software, previously bundled with hardware, was altered considerably beginning in the mid- to late 1960s. In particular, by the late 1960s, computer hardware began to become unbundled from software and associated maintenance. Moreover, whereas in the past, bundled computers were primarily rented on a monthly basis, by around 1968 or so the outright purchase of unbundled computers became the norm.

One implication of these computer hardware and marketing changes for the construction of price indexes is the following: If price indexes are to adjust properly for quality change, then it would seem to be important that the construction of indexes over the 1965–1972 time period should incorporate the effects of quality reductions associated with unbundling and that rental prices should be properly distinguished from purchase prices.

With this as background, let us now examine the pioneering study of demand for computers by Gregory Chow [1967]. The purpose of Chow's study was to explain the growth in demand for computer services in the United States over the 1955–1965 time period, in particular to separate out the effects on demand that would have occurred had technological change (quality improvements) not occurred from demand changes induced by technological change. To do this, it was necessary for Chow to construct a quality-adjusted price index for computer services, using hedonic price analysis and multiple regression techniques. Incidentally, since Chow's data spanned the time in which computers were rented, his measure of price is the rental price per month in thousands of dollars. Moreover, all his data come from an era in which computer software and hardware were bundled.

Recognizing that it would be impossible to obtain measures of all relevant quality variables, Chow chose but three characteristics and hoped that any omitted variables would be very highly correlated with the variables that he included.

The first variable chosen was multiplication time, computed as the average time required to obtain and complete the multiplication instruction, in microseconds. Chow expected this multiplication time variable, named MULT, to have a negative effect on computer rental price. Presumably, the MULT variable measures one aspect of the speed of the computer.

GREGORY C. CHOW

A Pioneer in Econometrics

Although Gregory C. Chow is undoubtedly best-known to econometrics students as developer of the widely used "Chow test" for parameter equality in differing data samples, his contributions have spanned a wide range of other topics as well. Chow's 1967 *American Economic Review* article on the demand for computers, discussed in detail in this chapter, is recognized as the first hedonic price analysis of quality changes embodied in computers; his work on using optimal control theory in dynamic economic models and his research on computational algorithms for econometric estimators are also regarded as seminal.

Born in Macau, South China, in 1929, Chow emigrated to the United States in the late 1940s. He received a B.A. degree from Cornell University in 1951 and M.A. (1952) and Ph.D. (1955) degrees from the University of Chicago, all in economics. After initiating an academic career at the Massachusetts Institute of Technology (1955–1959) and Cornell University (1959–1962), Chow moved in 1962 to the IBM Thomas J. Watson Research Center in Yorktown Heights, New York, where he served as Staff Member and Manager of Economic Models. In 1970, Chow returned to academia, becoming Professor of Economics and Director of the Econometric Research Program at Princeton University.

In the last decade, much of Chow's attention has focused on economic issues in the People's Republic of China (PRC). He has served as Chairman of the American Economic Association Committee on Exchanges in Economics with the PRC, has taught in the PRC on numerous occasions, holds honorary professorships and an honorary degree from Chinese universities, and has written econometric theory and economics textbooks that have been widely read by university students in China. Chow is a Fellow of the Econometric Society and has served on the editorial boards of numerous professional economics journals.

However, since computers are able to execute a wide variety of instructions, multiplication time might not necessarily be representative of the typical tasks executed on the computer. Other single-instruction speed measures could include addition time, but a more preferable measure might be a weighted composite of all of the instruction execution rates for a typical job mix (such as MIPS—millions of instructions per second). As is noted in the survey by Triplett [1989], there is some controversy among computer industry experts concerning the choice of speed measure, in part because it is thought that some measures favor one computer architecture (and therefore the manufacturer adopting it) over another.[26]

The second characteristic chosen by Chow as a measure of quality was memory size, called MEM, which was computed as the product of the number of words in the main memory (in thousands) and the number of binary digits per word, with allowances made for different types of digits.[27] Chow expected MEM to be positively related to quality and so expected the estimated coefficient of MEM in the hedonic price equation to be positive.

The third characteristic used by Chow was also related to speed and involved the average time required by the computer to retrieve information from the memory. This access time variable is named ACCESS. Chow predicted that the effect of ACCESS on rental price would be negative.

Chow obtained data for his study from a number of sources, including a published U.S. government survey of computer rentals and characteristics and issues of the monthly magazine *Computers and Automation*. For each year from 1955 to 1959, Chow obtained data on nine to eleven models rented (but not necessarily newly introduced) that year, while from 1960 to 1965 his data included only newly introduced models, which varied from a sample of 10 new models in 1960 to 18 in 1964.

In terms of empirical results, Chow reported that addition time was considered as a measure of speed instead of MULT but that results with it were slightly inferior. The estimated coefficients obtained by Chow based on separate, year-by-year regressions are reproduced in Table 4.1.[28]

Chow comments on his results as follows:

> Judging from the 11 cross section regressions for the individual years, memory size has a larger coefficient (in absolute value) than either access time or multiplication time. Three of the coefficients of multiplication time, and one coefficient of access time, have wrong signs, though they are small fractions of their standard errors. While the standard errors are large for many coefficients, as a result of the high correlations among the three explanatory variables and of the small sample sizes, the orders of magnitude of the three coefficients do not appear to have changed drastically through time. Note also that the intercept tends to be smaller for later years, but its decline is far from being uniform.[29]

Because his pre-1960 data was scarce, and to avoid mixing first- and second-generation computer models, Chow pooled his data for the years 1960 to 1965, constraining the slope coefficients on the three quality variables to be equal across all years but specifying dummy variable intercept terms for each year 1961 to 1965. The test statistic corresponding to the null hypothesis that these slope coefficients were equal across the six years suggests nonrejection of the null hypothesis; Chow reports a test-statistic of 0.74, which is considerably less than the critical value of the F-statistic at any reasonable level

Table 4.1 Chow's Estimated Hedonic Price Equations for Computer Services, 1955–1965: Estimated Standard Errors in Parentheses (All variables in natural logarithms)

Year	Intercept Term	Multiplication Time	Memory Size	Access Time	R^2	s^2	Number of Observations
1955	2.027	0.0108	0.4297	−0.2895	0.947	0.0461	9
		(0.1021)	(0.1530)	(0.0618)			
1956	1.675	−0.0505	0.4495	−0.1991	0.890	0.2081	11
		(0.1911)	(0.1624)	(0.1076)			
1957	0.140	0.0549	0.5651	−0.2187	0.941	0.1476	10
		(0.1596)	(0.1481)	(0.0807)			
1958	0.542	−0.0171	0.5311	−0.1617	0.976	0.0972	10
		(0.0891)	(0.0697)	(0.0565)			
1959	2.489	−0.2116	0.3562	−0.1270	0.993	0.0360	10
		(0.0366)	(0.0395)	(0.0337)			
1960	1.205	−0.1523	0.4234	−0.1208	0.943	0.1924	10
		(0.1009)	(0.1797)	(0.0783)			
1961	0.005	−0.0615	0.5507	−0.1755	0.944	0.1159	12
		(0.0729)	(0.1078)	(0.0519)			
1962	−2.404	0.0786	0.8264	−0.2571	0.916	0.2414	11
		(0.1411)	(0.1525)	(0.1167)			
1963	−0.801	−0.0675	0.5750	−0.0412	0.951	0.0794	15
		(0.0690)	(0.0732)	(0.1228)			
1964	−1.590	−0.1486	0.6867	0.0412	0.895	0.0978	18
		(0.0525)	(0.0754)	(0.1048)			
1965	−1.354	−0.0411	0.5778	−0.1465	0.877	0.2518	16
		(0.0779)	(0.0821)	(0.0999)			
Pooled Run:							
1960–1965	−0.1045	−0.0654	0.5793	−0.1406	0.908	0.1476	82
		(0.0284)	(0.0354)	(0.0293)			
	$-0.1398 \cdot D_{61}$	$-.4891 \cdot D_{62}$	$-0.5938 \cdot D_{63}$	$-0.9248 \cdot D_{64}$		$-1.163 \cdot D_{65}$	
	(0.1665)	(.1738)	(0.1661)	(0.1663)		(0.166)	

Note: D_{61}, D_{62}, D_{63}, D_{64}, and D_{65} are dummy variables for the years 1961–1965.

Source: Data from Gregory C. Chow, "Technological Change and the Demand for Computers," *American Economic Review*, Vol. 57, No. 5, December 1967, pp. 1117–1130.

of significance. Results from this pooled regression are presented in the bottom rows of Table 4.1.

A number of points are worth noting. First, in spite of strong correlations among the explanatory variables, each of the coefficients on the three quality variables, MULT, MEM, and ACCESS, is statistically significant, the MEM variable having a particularly large implied t-statistic (0.5793/0.0354 = 16.36). Second, since the regression involves logarithms of both the dependent and explanatory variables, the estimated coefficients can be interpreted directly as elasticities. The three elasticities are estimated to be 0.58 for MEM, −0.14 for ACCESS, and −0.07 for MULT. Third, coefficients on the dummy variables decrease uniformly as time increases, reflecting sustained price declines for computers, adjusted for quality change. An examination of these coefficients reveals that the price decline is particularly large from 1961 to 1962 (corresponding with the substantial market penetration of second-generation solid-state computers); another considerable decline in quality-adjusted price occurred in 1964, coinciding with price reductions on existing models following the announced introduction of the new IBM Series 360 models.

Quality-adjusted price indexes for computers could be computed in a number of ways. Chow suggests choosing a base year, say, 1960, and computing the base period quantity of computer services as the fitted value of the regression equation (with the −0.1045 intercept for 1960), using the arithmetic mean of the model characteristics for that year as measures of MULT, MEM, and ACCESS. Following the procedure completely analogous to that described for automobiles in the previous section of this chapter beneath Eq. (4.11), the average quantities of (quality-adjusted) computer services for other years are then computed, using the same 1960 intercept but replacing 1960 values of the characteristics with values for each of the models introduced in each year, 1961 to 1965. The quality-adjusted price index for each model could then be computed simply as the rental price divided by the above model-specific quantity-quality index. To calculate an aggregate price index for the year over all models, Chow simply employed an arithmetic average over each of the models introduced that year.[10]

An alternative procedure is much more direct and simply involves taking antilogarithms of the estimated coefficients of the dummy variables in the bottom row of Table 4.1. Normalizing the base year value to unity in 1960, one obtains a time series of quality-adjusted price indexes over the 1960–1965 time period, presented in the middle column of Table 4.2. This hedonic price index computed directly from the regression coefficients can be compared with that obtained using Chow's first suggested procedure, which is presented in the final column of Table 4.2. A comparison of these two columns indicates that in this case the two alternative methods outlined above for computing quality-adjusted price indexes give very similar results.

The above quality-adjusted price indexes can be used to compute their average annual growth rate (AAGR). When this is done for the directly com-

Table 4.2 Quality-Adjusted Price Indexes for Computers, 1960–1965, Based on Chow's Dummy Variable Coefficient Estimates and on Chow's Arithmetic-Weighted Procedure

Year	Estimated Coefficient	Price Index (Antilogarithm)	Price Index* (Arithmetic-Weighted)
1960		1.0000	1.0000
1961	−0.1398	0.8695	0.8438
1962	−0.4891	0.6132	0.6414
1963	−0.5938	0.5522	0.5330
1964	−0.9248	0.3966	0.3906
1965	−1.163	0.3125	0.3188

*Entries in the final column are taken from Chow [1967, Table 2, p. 1124], normalized to unity in 1960.

puted hedonic price index, one finds that the AAGR is approximately −20.8% per year, which implies that the quality-adjusted price index for computers declined approximately 21% per year over the 1960–1965 time period. Such a result is, of course, dramatically different from that implicitly assumed by the U.S. Bureau of Economic Analysis (BEA) until 1986, namely, that the price index for computers was constant at 1.000 over the entire 1953–1985 time period.[11]

Chow's research on the demand for computers marked the beginning of a substantial number of studies estimating quality-adjusted price indexes for computers. These studies have recently been surveyed by Triplett [1989].[12]

Triplett divides the various hedonic price studies on computers into those using data before 1972 and those using post-1972 data. With respect to the pre-1972 studies, Triplett notes that none reports any attempt to deal with the consequences of unbundling, which began to occur in the late 1960s. As a result, Triplett argues that the price indexes for the late 1960s and early 1970s estimated by the hedonic method quite likely overstated quality improvements, although the size of the bias is unknown. Triplett conjectures that it is conceivable that computer prices, quality-adjusted, actually rose slightly in the late 1960s or early 1970s.

After critically surveying a number of empirical studies, Triplett combines their hedonic price index estimates judgmentally, using weights that reflect what he calls "best practice" research criteria, such as quality of the underlying data sources, choice of index computation method used, and investigator effects. This yields a most interesting set of results, reproduced here in Table 4.3.

A number of comments are worth noting. First, a striking result in Table 4.3 is that the quality-adjusted price of computers declined every year from 1953 to 1972. Second, and even more striking, by 1972 a computer's quality-adjusted price was approximately only 1% of what it cost when computers first came on the market in 1953. Third, the advent of second-generation computers in 1958–1959 set off an accelerated rate of price decreases of about

Table 4.3 Triplett's "Best Practice" Research Price Index for Computers, 1953-1972

Year	Price Index (1965 = 100)	Annual % Change	Year	Price Index (1965 = 100)	Annual % Change
1953	1320		1963	183.0	−23.6
1954	1139	−13.7	1964	139.0	−24.2
1955	1010	−11.3	1965	100.0	−27.8
1956	862	−14.7	1966	38.0	−61.5
1957	761	−11.8	1967	26.9	−30.1
1958	689	−9.4	1968	24.3	−9.7
1959	591	−14.2	1969	24.2	−0.4
1960	435	−26.4	1970	23.3	−3.7
1961	332	−23.7	1971	18.1	−22.3
1962	239	−27.9	1972	14.8	−18.2

Source: Data from Jack E. Triplett, "Price and Technological Change in a Capital Good: A Survey of Research on Computers," Chapter 4 in Dale W. Jorgenson and Ralph Landau (eds.), *Technology and Capital Formation*, Cambridge, Mass.: MIT Press, 1989, Table 4.6A, p. 176.

25% per year, which increased dramatically to over 60% when third-generation computers were delivered in 1966. Over the 1967–1970 time period these price decreases slowed considerably; they then picked up again in 1971–1972 with the introduction of the IBM Model 360 series. Note, however, that failure to account for the unbundling of computers implies that the post-1968 price indexes may be biased downward. Fourth and finally, the AAGR of the quality-adjusted price index for computers over the entire 1953–1972 time period is about −27%, implying that quality-adjusted price decreases in computers over this time period have occurred at a prodigious rate.

Turning now to the post-1972 time period, we begin by noting that a substantial number of empirical studies examining computer price movements have been published over this time period. Although Triplett surveys these in considerable detail, here we confine our attention to just one hedonic price study, the IBM analysis published by Cole et al. [1986], which in turn formed part of the basis of the official computer price index later published by the U.S. Department of Commerce, Bureau of Economic Analysis.

One aspect of the Cole et al. study that is worthy of special note was its focus on the individual components or "boxes" of a computer system, rather than on the system as a whole. In particular, Cole et al. separately examined computer processors, intermediate and large (hard) disk drives, printers, and general-purpose displays (keyboards and monitors).

Although they experimented with a number of alternative functional forms (e.g., log-log, semilog, and linear), Cole et al. obtained preferred results with the log-log specification. For the computer processors the quality characteristics chosen were speed (MIPS, or millions of IBM 370-equivalent instructions per second) and memory (in megabytes); for disk drives the characteristics used were speed and capacity. While capacity was relatively straightforward to measure (the number of megabytes that could be stored on the disk drive), speed (in units of kilobytes per second) was computed as 1 over the sum of three elements: average seek time (the average time for the read/write head to locate and arrive at the correct track on the disk) plus average rotation delay (the time required by the disk to rotate so that the read/write head is lined up at the correct point on the track) plus the transfer rate (the time required to transfer the data between the drive and the main memory once the correct position on the disk has been located).[11] Data were taken from a number of sources, including IBM sales manuals and trade and general press sources such as *Datamation* and *Computerworld*. Prices for the various models are list prices for a quantity of one and so do not necessarily correspond with transactions prices, particularly in the case of large-volume discounting.

Since they employed a log-log specification, Cole et al. were able to interpret the coefficient estimates on the characteristic variables as elasticities of price with respect to quality characteristics. One hypothesis that they examined in detail was what they called homogeneity, by which they meant the hypothesis that the sum of the elasticities (coefficient estimates) on the quality characteristic variables equaled 1. Under this type of homogeneity, a doubling in the values of each of the characteristic variables would double the price. Significantly, for each of the four types of computer equipment that Cole et al. examined, the null hypothesis that the characteristics coefficients summed to 1 could not be rejected.

On the basis of their hedonic regression results, Cole et al. constructed a number of alternative price indexes. Here we confine our discussion to their estimates for processors and intermediate-large disk drives, estimates that are reproduced in columns 1–4 of Table 4.4.

The most striking result that is observed in Table 4.4 is that the traditional matched model procedure for accounting for quality change appears to be woefully inadequate. For example, while the matched model procedure generates an AAGR of −8.5% for computer processors, the hedonic regression procedure yields a much larger (in absolute value) AAGR of −19.2%; for disk drives, the matched model and hedonic regression procedures yield price indexes that grow at an AAGR of −6.9% and −16.8%, respectively.

Finally, in column 5 of Table 4.4 we reproduce from Cartwright [1986] the new official U.S. Department of Commerce, Bureau of Economic Analysis, price index for the commodity aggregate of computers and computer-peripheral equipment types, based largely on hedonic regression procedures.[14] Note that this price index continues the steady decline over time first revealed earlier for the 1953–1972 time period in Table 4.3. Over the 1972–1984 era, the AAGR of this quality-adjusted price index is −13.8%.

If one combines the results from Table 4.3 for the 1953–1972 time interval with those of Table 4.4 for the 1972–1984 epoch, one finds that, quality adjusted, computers that cost $531.88 in 1953 cost only $1.00 in 1982; in

Table 4.4 Price Indexes for Processors and Disk Drives Based on the Cole et al. Study* and New Official Hedonic-Based BEA Price Indexes for Computers** (1982 = 100)

	Processors		Disk Drives		Computers
Year	(1) Matched Model	(2) Hedonic Regression	(3) Matched Model	(4) Hedonic Regression	(5) New Official BEA Price Index
1972	214.1	990.1	201.7	427.4	408.1
1973	214.6	1047.5	200.9	429.5	369.3
1974	219.9	814.8	154.5	345.3	291.1
1975	228.9	792.1	143.4	313.2	265.1
1976	223.6	778.2	134.0	291.5	231.1
1977	183.5	499.0	133.5	150.0	199.7
1978	147.3	262.4	131.1	147.0	169.3
1979	136.4	242.6	107.7	111.0	146.2
1980	115.4	177.2	91.0	96.2	117.5
1981	111.1	112.9	92.9	96.6	107.4
1982	100.0	100.0	100.0	100.0	100.0
1983	89.7	90.1	86.5	54.3	77.1
1984	73.7	77.2	85.1	46.9	68.5
AAGR 1972–1984	−8.5	−19.2	−6.9	−16.8	−13.8

*Source: Cole et al. [1986, Table 7, p. 49].
**Source: Cartwright [1986, Table 1, p. 8].

other words, what would have cost more than half a million dollars in 1953 cost only $1000 in 1984. Moreover, since the calculations in Cole et al. and Cartwright involve only mainframe and minicomputers and exclude personal (micro) computers, it is possible that this price index understates the amount of quality improvement.

This concludes our survey of empirical hedonic research on price indexes for computers. We now change our focus and consider several econometric issues that arise in the estimation of hedonic regression equations.

4.5 ECONOMETRIC ISSUES IN THE ESTIMATION OF HEDONIC PRICE EQUATIONS

Our survey of empirical hedonic research on price indexes for computers has already raised a number of econometric issues. In this section we briefly consider some other important topics.

4.5.A Heteroskedasticity

One econometric issue that has received some attention in the hedonic price literature concerns heteroskedasticity of the disturbance terms. Suppose, for example, that data consist of average prices of each computer model and that the various models have rather different sales volumes. Let the disturbance term u_i in the regression equation

$$Y_i = \beta_0 + \beta_1 \cdot X_{1i} + \beta_2 \cdot X_{2i} + \cdots + \beta_K \cdot X_{Ki} + u_i \qquad i = 1, \ldots, N$$

originally involving N individual computer observations be distributed normally with mean zero and variance σ^2, but let the M observations consist of average prices for each of the M models, where $M < N$. Denote the volume of sales for the mth model as S_m. When M model-specific averaged data observations are used rather than the original data for each of the N computers, the variance of the disturbance term u_i^* is no longer σ^2 but instead equals σ^2/S_m. This implies a heteroskedastic disturbance term, large-volume models having smaller disturbance variances than models with low-volume sales.

In order that estimates of the parameters be efficient and that estimated standard errors be consistent, it is necessary to use generalized or weighted least squares rather than ordinary least squares. Intuitively, in this case, generalized least squares weights the large-volume, low-disturbance-variance models more and the low-volume, high-disturbance-variance models less than does ordinary least squares. Note, however, that in this particular example, if one first transforms each of the variables (including the vector of ones for the intercept term) by multiplying them by $\sqrt{S_m}$ and then performs ordinary least squares on the transformed data, the results obtained will be numerically equivalent to employing generalized or weighted least squares on the untransformed data. For further details on generalized least squares, see your econometric theory textbook.

4.5.B Choice of Functional Form

Several times in the previous sections we noted that, on the basis of economic or other theory, few if any restrictions were placed on the functional form of the hedonic price equation. While Waugh considered only the linear form, Court compared the semilog form with the linear one and noted that on the basis of goodness-of-fit criteria, with his automobile data the semilog form was preferable. Similarly, Cole et al. compared results based on the linear, semilog, and log-log specifications and, on the basis of their data for four different types of computer equipment, found that in general the log-log specification was preferred. It should be noted here that a comparison of goodness of fit from the various functional forms is not necessarily straightforward, since explaining variations in the natural logarithm of price is not the same as explaining variations in price.

Although a full discussion is beyond the scope of this chapter, it is worth mentioning here briefly that there is a statistical basis that can be used to compare alternative functional forms, and not just the log-log, semilog, and linear specifications. This procedure is known as the Box-Cox or Box-Tidwell transformation.[35] The Box-Cox procedure involves transforming a variable from X_i to X_i^* as follows:

$$X_i^* = \frac{X_i^\lambda - 1}{\lambda} \tag{4.12}$$

where λ is a parameter to be estimated. When $\lambda = 1$ for all variables (Y and the X's), the functional form is linear, and in the limit as $\lambda \rightarrow 0$ for each variable, $Y_i^* \rightarrow \ln Y_i$ and the $X_i^* \rightarrow \ln X_i$, implying a log-log specification. One can also specify a different λ for Y_i than for all of the X_i right-hand variables, in which case one would have a mixed specification; if the λ for Y were restricted to 0 and that for all the X's to 1, a semilogarithmic functional form would result. In the Box-Tidwell procedure the individual X's are permitted to have differing λ's as well.

An important point here is that λ need not be restricted to values of 0 or 1 but can take on a wide variety of other values, including those outside the 0–1 interval.[36] In fact, in his survey, Triplett [1989] notes that the log-log specification used in many econometric studies is inconsistent with certain a priori knowledge of the computer industry. He suggests that values of λ other than 0 or 1 should also be investigated, including negative values.[37]

4.5.C Choice of Variables, Make Effects, and Effects of Omitted Variables

The hedonic hypothesis essentially involves treating varieties of products as alternative bundles of a smaller number of characteristics. These characteristics should of course reflect measures of quality. But how should measures of quality be chosen? In the case of computers, Cole et al. report that the IBM study group spent considerable effort in understanding the views of computer industry engineering design and marketing personnel and that on the basis of such discussions they settled on a number of quality variables. This approach is attractive, since knowledge of the particular industry is most useful in choosing measures of quality.

As Chow, Cole, and others have freely acknowledged, however, it is impossible to specify all the relevant quality variables entering an hedonic price equation for computers. In general, unless the omitted variables are either perfectly correlated or perfectly uncorrelated with each of the included variables, the omission of significant quality variables can result in biased estimates of the parameters.

Some have argued that one particularly important quality variable that is typically omitted from computer hedonic price equations concerns the reliability of the model, or the service and maintenance it may require. Presumably, this variable is omitted because of difficulty in obtaining an accurate measure of it. However, if such a quality were associated with the manufacturer of the model, and if it were assumed that this quality effect is constant over time, then one could incorporate it into the hedonic equation by specifying dummy variables for various manufacturers. When this is done, estimates of the resulting parameters are often called "make effects."[38]

More generally, it is often the case that the quality variables employed in hedonic regression equations are not in themselves measures of quality but are presumed to be highly correlated with consumers' perceptions of qualities. In the automobile study by Court, for example, the weight of the auto model in pounds was used as a measure of quality. Consumers surely do not judge the quality of an auto by its weight, yet in fact weight has often been highly correlated with other quality attributes, such as safety and power.

This raises the issue of how one can properly estimate parameters of the hedonic price equation when the quality attributes are unobserved or are measured with error. There is a great deal of literature elsewhere in econometrics on coping with measurement error or unobserved variables, but that literature is only now finally beginning to be applied to the estimation of hedonic price equations.[39] We can expect much more research on this topic in the future.

4.5.D Identification of Underlying Supply and Demand Functions

Earlier in this chapter it was noted that since price-quality observations can be viewed as the market outcome of underlying supply-demand relations for characteristics, shifts in either function could result in volatile parameter estimates in the estimated hedonic price equation. To be specific, recall that implicit prices of the characteristics can be computed as partial derivatives of the price of the product with respect to the level of the characteristic. With a linear functional form, these derivatives are simply the parameters, and in that case the parameters provide direct estimates of the implicit prices. With other functional forms, such as the semilog or log-log specifications, these derivatives can depend on levels of the characteristics and the product price as well as the parameter estimates. This therefore suggests that tests for parameter stability in the hedonic price equation are closely related to tests for shifts in the underlying supply-demand relationships for characteristics.[40]

This type of reasoning has led a number of researchers to extend the hedonic price framework and to attempt to estimate, in addition to the hedonic price equation, the underlying supply and demand equations for characteristics. However, this more ambitious analysis of hedonic markets raises a number of important econometric issues.

Note first that the estimated hedonic price equation contains three pieces of information: the price of the product, the quantities of the characteristics, and the implicit prices of the characteristics. This information makes it possible to define the budget constraint facing consumers; for example, how much of characteristic i must be given up in order to obtain more of characteristic j, product price being held constant. Second, since with many functional forms the implicit prices depend on the levels of the characteristics, the slope of the budget constraint is not necessarily constant, and so the budget constraint is nonlinear. This contrasts with the usual case dealt with in economics texts, in which the budget constraint for products is linear.

Owing in large part to nonlinearity of the budget constraint, it turns out that in general it is very difficult, and at times even impossible, to obtain consistent estimates of the supply and demand functions underlying the hedonic price equation. This has been shown in important papers by Sherwin Rosen [1974] and Dennis Epple [1987]; also see Timothy J. Bartik [1987].

There are, however, some special cases in which one can interpret these implicit prices as reflecting directly the marginal costs of production or the valuations of consumers. Suppose first that the supply of characteristics is fixed, that is, supply is perfectly price inelastic. In such a case, demand curves for the various characteristics will intersect with vertical supply curves at the implicit prices estimated by the hedonic price equation. Hence in such cases, implicit prices will reflect the market's valuations of the characteristics. If in addition it is assumed that all consumers are alike, then the implicit prices reflect valuations of the representative consumer. In practice, empirical hedonic studies based on perfectly inelastic supply assumptions have often dealt with secondhand markets such as those for automobiles, trucks, or housing.[41]

Alternatively, suppose that supply curves for characteristics are perfectly flat and elastic, firms are identical, and markets are competitive. In such cases the demand curves for the various characteristics will always intersect with the supply curves at an implicit price that is equal to the average (and marginal) costs of production, since with competitive markets, price equals average and marginal costs.[42] Incidentally, the perfect competition assumption can be relaxed to that of a constant markup situation; for an empirical implementation, see Makoto Ohta [1975].

In general, however, the strong results reported by Rosen, and especially by Epple, indicate that while hedonic prices reflect the shape of budget constraints, identification of the underlying supply and demand functions for characteristics is very difficult and that a great deal of care is required in both the specification and the estimation of equations in order to obtain a valid inference. The subtleties involved become even more complex if one specifies that markets for new products can be in temporary disequilibrium in the sense that supply prices are not necessarily instantaneously adjusted to equality with consumers' valuations.[43]

4.5.E Final Comments

In this section we have briefly raised a number of important econometric issues that are involved in the estimation and interpretation of parameters in hedonic price equations. Exciting features of the hedonic price framework are that its practical importance is obvious, it can be implemented relatively easily, and yet it raises a host of very significant and difficult econometric issues. Therefore the analysis of hedonic prices provides both beginning and advanced econometricians with opportunities for challenging research. With that as background we now take a hands-on approach and involve you in the estimation and interpretation of hedonic price equations.

4.6 HANDS ON WITH HEDONIC REGRESSIONS, PRICE INDEXES, AND COMPUTERS

The purpose of the following exercises is to help you gain an empirical understanding of hedonic regression equations, of price indexes constructed from estimated hedonic regression equations, and of the importance of selected characteristics on prices of computers. Although you might not experience hedonistic pleasures from these exercises involving hedonic regressions, in fact they are very useful, and you might even enjoy them!

Exercise 1 is particularly enlightening; in it you attempt to replicate Waugh's pioneering study and find that replication is not possible. This is a useful (and, unfortunately, not uncommon) experience in applied econometrics. This leads you to examine his data more carefully. In Exercise 2 you perform a number of simple and multiple regression estimations using Waugh's data, and then you examine relationships among their R^2 measures, as well as coefficients of determination and correlations.

In Exercise 3 you compute a number of alternative price indexes for computers, using Chow's data set, multiple regression techniques, and dummy variables. You also test an hypothesis involving the specification of the MEM variable. Again, you will experience some problems in attaining complete replication of Chow's original findings. Then in Exercise 4 you replicate (with success!) the findings reported by Cole et al. in their analysis of hard disk drives of computers, findings that were later adopted in part by the U.S. Department of Commerce for its official computer price index. You will test for homogeneity of the characteristics and will also examine alternative ways of modeling price changes over time.

Whether the hedonic coefficients are stable over time is an important issue; therefore in Exercise 5 you have the opportunity to test this hypothesis, using a variety of parameter equality tests, including the well-known Chow test. The application here involves examining parameter stability over the first and second generations of computer models and employs Chow's data. Then in Exercise 6 you investigate a different way of constructing price indexes based on hedonic equations, namely, using adjacent year regression procedures and Chow's data.

Finally, for students with more advanced backgrounds, in Exercise 7 you engage in an examination of choice of functional form, using the Box-Cox estimation method and your choice of either the Waugh asparagus data or the Chow computer data.

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In the data diskette provided (have you made a backup?), you will find a subdirectory called CHAP4.DAT with data files. In these data files, three data series are provided, including the asparagus data from the original Waugh study (in a file named WAUGH), the data series collected and used by Chow in his 1967 study of demand for computer services (CHOW), and a portion of the large data set used by Cole et al. in the IBM study for the U.S. Department of Commerce. The Cole et al. data here are those for intermediate and large (hard) disk drives and are found in the file named COLE.

Note that before the data diskette can be used, the data files must be properly edited and formatted, depending on the requirements of your particular computer software. For further information, refer back to Chapter 1, Section 1.3. MAKE SURE THAT ALL DATA FILES TO BE USED IN THE EXERCISES BELOW ARE PROPERLY FORMATTED.

EXERCISES

EXERCISE 1: Examining Waugh's 1927 Asparagus Data

In a number of exercises in this book you will be asked to replicate a researcher's reported empirical findings. The appropriate data will be provided to you, and unless your software is flawed, you should be able to replicate successfully previously reported results. In some cases, however, it will not be possible to achieve a complete replication or reconciliation of findings, and this will require you to dig further and examine the underlying data more closely. That is what we ask you to do in this exercise. The purpose of this exercise, therefore, is to involve you in an important part of the scientific method, namely, to attempt to replicate others' empirical findings.

In your data diskette subdirectory CHAP4.DAT is a file called WAUGH, which contains 200 data points on four variables: (1) the relative price per bunch of asparagus, named PRICE; (2) the number of inches of green color on the asparagus (in hundredths of inches), called GREEN; (3) the number of stalks of asparagus per bunch, denoted NOSTALKS; and (4) the variation in size (the interquartile coefficient) of the stalks, denoted DISPERSE.[44]

(a) Using these data, estimate the parameters of the multiple regression equation in which PRICE is regressed on a constant term, GREEN, NOSTALKS, and DISPERSE. Compare the parameter estimates that you obtain with those reported by Waugh, reproduced in Eq. (4.3) of this chapter. Which parameter estimates differ the most from those of Waugh?

(b) Since the results differ, further investigation appears to be warranted. In his Appendix, Waugh [1929, Table 4, p. 144] reports summary statistics of his underlying data. In particular, he reports the arithmetic means of the variables PRICE, GREEN, NOSTALKS, and DISPERSE to be 90.095, 5.8875, 19.555, and 14.875, respectively. Compute means of these variables. Are his statistics consistent with those based on the data in your file WAUGH? Do you have any hunches yet on the source of the inability to replicate Waugh's findings?

(c) Waugh's Appendix also provides statistics on the product moments (variances and covariances) of the four variables, as follows:

	PRICE	GREEN	NOSTALKS	DISPERSE
PRICE	1063.64	3430.89	−100.92	−82.35
GREEN		24317.19	−17.01	−154.54
NOSTALKS			61.33	25.51
DISPERSE				83.07

Using your computer software and the data provided in the file WAUGH, compute the moment matrix and compare it to Waugh's, as reproduced above. Notice that the sample variances for the variables GREEN and DISPERSE are very similar to those reported by Waugh,[45] they are not quite as close for NOSTALKS, and are very different for PRICE. Are all your covariances larger than those reported by Waugh, or does the relative size vary? Does there appear to be any pattern to the differences that might help to reconcile the findings?

(d) Even though it does not appear to be possible to reconcile Waugh's data with his reported estimates of regression coefficients, are any of his principal *qualitative* findings concerning the effects of variations in GREEN, NOSTALKS, and DISPERSE affected? How different are your findings from his concerning the *quantitative* effects of one-unit changes in each of the regressors on the *absolute* price per bunch of asparagus? (To do these calculations, you will need to refer back to Section 4.2 and will also need to know that the average market quotation PM_t was \$2.782.) Comment also on the statistical significance of the parameter estimates.

(e) Do you have any final thoughts on why results differ? (Hint: Compute least squares estimates using his estimated variances and covariances, reproduced above.)

EXERCISE 2: Exploring Relationships among R^2, Coefficients of Determination, and Correlation Coefficients

Earlier in this chapter we noted the extensive use Waugh made of his estimated coefficients of determination and how he apparently erred in interpreting his results. The purpose of this exercise is to gain an understanding of relationships among the various coefficients of determination, R^2, and correlation coefficients, as well as to comprehend better the implications of the extent of correlation among regressors.

(a) In the data file WAUGH of subdirectory CHAP4.DAT you have observations on the variables PRICE, GREEN, NOSTALKS, and DISPERSE. Using your computer software, compute simple correlations between each of these variables. The correlation matrix that you obtain should be the following:

	PRICE	GREEN	NOSTALKS	DISPERSE
PRICE	1.00000	0.74834	−0.40656	−0.32464
GREEN		1.00000	−0.01403	−0.12605
NOSTALKS			1.00000	0.35003
DISPERSE				1.00000

Which variables are most highly correlated? Which variables are almost orthogonal?

(b) Run three simple regressions, PRICE on GREEN, PRICE on NOSTALKS, and PRICE on DISPERSE, where each regression also includes a constant term. Take the R^2 from each of these three simple regressions, and compute its square root. Then compare its value with the appropriate correlation coefficient reported in the first row of the above table. Why are they equal (except for sign)? Now suppose you had messed up and had inadvertently run the "reverse" regressions, GREEN on PRICE, NOSTALKS on PRICE, and DISPERSE on PRICE. What R^2 measures would you have obtained? Why do they equal those from the "correct" regressions?

(c) Notice the value of the R^2 measure from the simple regression of PRICE on GREEN, computed in part (b). What do you expect to happen to this value of R^2 if you now add the regressor NOSTALKS, that is, run a multiple regression equation with PRICE on a constant, GREEN, and NOSTALKS? Why? Given the correlation between the GREEN and NOSTALKS variables shown in the above table, do you expect the change in R^2 to be large or small? Why? Run this regression equation, and check to see whether your intuition is validated. Then comment on the change in the R^2 value from the simple regression of PRICE on GREEN or PRICE on DISPERSE when PRICE is regressed on both GREEN and DISPERSE; is this change consistent with the sample correlation between GREEN and DISPERSE? Similarly, what is the change in the R^2 value from the simple regression of PRICE on NOSTALKS or PRICE on DISPERSE when PRICE is regressed on both NOSTALKS and DISPERSE? Is this change consistent with the sample correlation coefficient between NOSTALKS and DISPERSE? Why?

(d) In all three cases considered in part (c), the R^2 from the multiple regression (with two regressors in addition to the constant) is less than the sum of the R^2's from the corresponding two simple regressions. Is the R^2 from the multiple regression equation with all three regressors (GREEN, NOSTALKS, and DISPERSE) greater than or less than the sum of the R^2 from the three simple regressions? *Note:* It might be tempting to conclude from this that the R^2 from a multiple regression with a constant term and K regressors is *always* less than or equal to the sum of the R^2 values from the K simple regressions. However, this is not always the case, as has been shown in an interesting theoretical counter example by Harold Watts [1965] and validated empirically by David Hamilton [1987]. (See Exercise 3 in Chapter 3 in this book for further details.)

(e) Using Eq. (4.5) in this chapter to compute separate coefficients of determination, based on the regression coefficient estimates reported by Waugh and reproduced in Eq. (4.3), see whether you can replicate Waugh's reported coefficient of determination values for the GREEN, NOSTALKS, and DISPERSE variables as 0.40837, 0.14554, and 0.02133, respectively. You should be able to replicate Waugh for NOSTALKS and DISPERSE but not for GREEN. Waugh [1929, p. 113] states: "The sum of the coefficients of determination is .57524, indicating that 57.524 per cent of the squared variability in the percentage prices is accounted for by the three factors studied." Is this correct? What should Waugh have stated instead? Why?

(f) As in part (a) of Exercise 1, estimate parameters in the multiple regression equation of PRICE on a constant, GREEN, NOSTALKS, and DISPERSE. Note the value of the R^2 from this regression, and then compute and retrieve the fitted or predicted values. Now run a simple regression equation in which the dependent variable is PRICE and the regressors include a constant and the fitted value from the previous regression equation. Compare the R^2 from this regression to that from the first regression. Why does this result occur? Why is the value of the estimated intercept term zero and the estimated slope coefficient unity in this regression?

EXERCISE 3: Constructing Alternative Price Indexes for Computers Based on Chow's Data

The purpose of this exercise is to construct a price index for computers using hedonic regression techniques and then to assess the sensitivity of the price index to changes in the specification of the underlying hedonic regression equation.

In the data file CHOW in the subdirectory CHAP4.DAT you will find data series consisting of 137 observations on 11 variables. These variables (not necessarily in the same order as they appear in the data file) include the number of new installations of that computer model in that year (VOLUME), the monthly rental of computers (RENT), the number of words in main memory, in thousands (WORDS), the number of binary digits per word (BINARY), the number of equivalent binary digits (DIGITS), the average time required to obtain and complete multiplication or addition instructions (denoted as MULT and ADD, respectively), the average time required to access information from memory (ACCESS), the year in which the model was introduced (YEAR), a dummy variable taking on the value of 1 if the model was manufactured by the IBM corporation (IBMDUM), and the number of the observation (ORDER). These data were provided by Gregory Chow.

(a) Construct the appropriate variables. In particular, take natural logarithms of the variables RENT, MULT, ACCESS, and ADD, and rename them using the prefix LN (e.g., LNRENT). Form the variable for memory space, MEM, as the product WORDS*BINARY*DIGITS, and then take the natural logarithm of this new MEM variable and call it LNMEM. Finally, construct the dummy variables D_{61}, D_{62}, D_{63}, D_{64}, and D_{65} that take on the value of unity if the model was introduced in the year 1961, 1962, 1963, 1964, or 1965, respectively, and otherwise are zero. Note that if a model was introduced in, for example, 1962, the value of the variable YEAR for that observation would be 62. Using the data from 1960 through 1965, and then from 1954 to 1959, compute and examine the correlation matrices measuring simple correlations among the above variables. Are the correlations among variables roughly the same over the two time intervals? Was Chow's concern over collinearity among regressors justified?

(b) Having constructed these data, replicate Chow by estimating parameters of the multiple regression equation of LNRENT on a constant term, D_{61}, D_{62}, D_{63}, D_{64}, D_{65}, LNMULT, LNMEM, and LNACCESS, using observations from 1960 through 1965 (observations 56 to 137 in the variable ORDER). Unless your software (or data construction procedures) is flawed, you should be able to obtain the same results as Chow reported, reproduced in the bottom rows of Table 4.1 in this chapter. Finally, normalize the price index for computers to 1.000 in 1960, take antilogarithms of the estimated coefficients on the dummy variables, and then form a price index covering the 1961–1965 time period. Compare this price index series to that reported in Table 4.2.

(c) Arguments can be made that for purposes of computational accuracy the number of equivalent binary digits per word (the product BINARY*DIGITS) might be more important than the number of words in memory (WORDS). Show that in Chow's logarithmic specification of the variable MEM in the hedonic price equation, the logarithms of these two variables (BINARY*DIGITS and WORDS) are implicitly assumed to have equal slope coefficient estimates. Now construct a new separate variable measuring word length, LENGTH = BINARY*DIGITS; then form the two separate logarithmic variables LNLENGTH and LNWORDS. Next, estimate parameters in the multiple regression equation of LNRENT on a constant term, D_{61}, D_{62}, D_{63}, D_{64}, D_{65}, LNMULT, LNLENGTH, LNWORDS, and LNACCESS, using observations from 1960 through 1965 (observations 56 to 137 in the variable ORDER). Test the null hypothesis that coefficient on LNLENGTH equals that on LNWORDS, using a reasonable level of significance. Is this null hypothesis rejected or not rejected? Which specification do you prefer, and why?

(d) Next construct dummy variables D_{55}, D_{56}, D_{57}, D_{58}, D_{59}, and D_{60} that take on the value 1 if the appropriate year is 1955, 1956, 1957, 1958, 1959, or 1960, respectively. Using the entire sample of 137 observations, estimate parameters in the multiple regression equation of LNRENT on the dummy variables D_{55} through D_{65}, LNMULT, LNMEM, and LNACCESS. On the basis of values of the estimated dummy variable coefficients, construct a price index for computers covering the 1954–1965 time period, normalized to unity in 1954. Compare this price index with the "best practice" index computed by Triplett, reproduced in Table 4.3. (You might want to renormalize one of the two series so that the base years are common.)

(e) In Section 4.5.A of this chapter it was noted that if the differing computer models range considerably in their volumes of sales, and if the pure data reflected arithmetic means over varying amounts of sales by model, then the disturbance terms may be heteroskedastic. Chow collected data on the number of computers installed by year for each model; in the data file CHOW this variable is named VOLUME. Using the pooled data over the 1960–1965 time period, follow the procedures outlined in Section 4.5.A, transform the variables appropriately (including the intercept and dummy variables), and then estimate parameters of the transformed model data by ordinary least squares. Are any of the parameter estimates affected significantly? What is the effect on the estimated standard errors of adjusting for this type of heteroskedasticity? Is the rationale for this type of heteroskedasticity correct, since LNRENT rather than RENT is the dependent variable? Why or why not?

EXERCISE 4: Price Indexes for Disk Drives: A Closer Look at the IBM Study

The purpose of this exercise is to replicate, interpret, and extend selected results reported by Cole et al. in the IBM study of price indexes for hard disk drives. Using data consisting of 91 observations on 30 devices marketed by 10 vendors over the 1972–1984 time period in the United States, Cole et al. obtained the following results, in which LN refers to the natural logarithm, PRICE is the list price, SPEED is 1 over the sum of average seek time plus average rotation delay plus transfer rate, CAP is the capacity of the disk drive in megabytes, the numbers in parentheses are t-statistics, and s is the estimated standard error of the residuals:

$$\underset{}{LNPRICE_i} = \text{Dummies} + \underset{(3.3)}{0.41}\, LNSPEED_i + \underset{(5.8)}{0.46}\, LNCAP_i + e_i$$

$$i = 1, \ldots, 91 \qquad R^2 = 0.844 \qquad s = 0.051$$

The data used by Cole et al. are found in the data file COLE within the subdirectory CHAP4.DAT. This file also contains a number of other variables, discussed in the README.DOC file of the CHAP4.DAT subdirectory. Further information can also be obtained by reading the article by Cole et al. in the January 1986 *Survey of Current Business*.

Very important note: After publishing their article, Cole et al. discovered several data errors. Three data corrections have been made since the original research was published. These data revisions affect parameter estimates. The data now appearing at the beginning of the COLE file reflect these corrections, while original values for these data are found in the last part of the COLE data file. Further information is available in the README.DOC data file of the CHAP4.DAT subdirectory.

(a) Using the original data, construct the variables LNPRICE, LNSPEED, and LNCAP, as well as dummy variables by year for each year from 1973 to 1984. Estimate parameters of the multiple regression model of LNPRICE on a constant, the 12 yearly dummies, LNSPEED, and LNCAP. You should be able to replicate successfully the Cole et al. results reproduced above.

(b) Now construct the same variables using the corrected data, and estimate parameters of the same regression equation. Compare the results. Are any of the parameter estimates affected in a substantial manner?

(c) Cole et al. report that in many cases they were unable to reject the null hypothesis of homogeneity, which they interpreted to imply that the sum of the estimated regression coefficients on LNSPEED and LNCAP equals unity. Since most computer regression software programs permit you to print out or retrieve the estimated variance-covariance matrix of the estimated coefficients, you should be able to obtain estimates of the variances and covariances of these two regression coefficients. Given your parameter and variance-covariance estimates from part (b), construct a 95% confidence interval for the sum of the regression coefficients on the LNSPEED and LNCAP variables. (You will need to use the variance of a sum rule—see any statistics text to refresh your memory.) Is the null hypothesis of homogeneity rejected? Why or why not? Comment on your test results.

(d) The model specification employed in parts (a) and (b) allows the annual rate of price decrease, quality adjusted, to vary over time. A more restrictive assumption is that this annual rate of price decrease is constant. Show that if one replaces the 12 dummy variables in part (a) or (b) with the single variable TIME, where TIME takes on the value 1 in 1972, 2 in 1973, . . . , and 12 in 1984, then such a model specification imposes the restriction that the annual rate of price decrease is constant. Generate the TIME variable, and then, using the corrected data and the variable TIME in place of the annual dummy variables, estimate such a model. Test the null hypothesis of constant rate of price decreases against the alternative hypothesis of differing rates of price decrease for each year. Do the data support the constant rate of price decrease assumption? Why or why not?

EXERCISE 5: Assessing the Stability of the Hedonic Price Equation for First- and Second-Generation Computers

In this exercise we assess the stability of the hedonic price equation for computers over time. One implicit hypothesis underlying the hedonic method is that goods such as computers can be viewed as the aggregate of a number of characteristics. Since firms supply various computer models embodying alternative combinations of characteristics and consumers demand them, the relationship between price and characteristics reflects the outcome of a market process. When dramatic technological changes occur, factor prices vary, or if consumer preferences change, the relationship between the overall price of the bundle and the individual characteristics might also change. The data to be used are in the file CHOW within the subdirectory CHAP4.DAT; names of variables are described at the beginning of Exercise 3 above.

(a) Conventional wisdom in the computer industry dates the first generation of computers as occurring from 1954 to about 1959 and the second generation as taking place between 1960 and about 1965. Chow [1967, p. 1123] reports that he tested the null hypothesis that the three "slope" coefficients were equal over the 1960–1965 time period and could not reject the null hypothesis; his F-test statistic was 0.74, much less than the critical value at any reasonable level of significance. Construct the appropriate variables as in part (a) of Exercise 3, and then estimate parameters in two models, one in which the slope coefficients are constrained to be the same in all years 1960–1965 (a pooled regression) and the other in which these coefficients are allowed to differ (separate, year-by-year regressions). You should be able to replicate Chow's results, reproduced in Table 4.1 of this chapter. Based on the sums of squared residuals from these regressions, test the null hypothesis that the slope coefficients are equal over the 1960–1965 time period. Be particularly careful in calculating the appropriate degrees of freedom for the F-test.

(b) Form appropriate dummy variables for each of the years from 1955 to 1959, and then repeat part (a) and test the null hypothesis that the slope coefficients are equal over the 1954–1959 era, first by running a pooled regression over the 1954–1959 data and then by doing year-by-year regressions, 1954 to 1959. Incidentally, the year-by-year results that you will obtain for 1955–1958 will differ somewhat from those reported by Chow and reproduced in Table 4.1; the reason for these discrepancies is unclear, although for years 1957 and 1958 the CHOW data set has only nine observations, whereas in Chow's [1967] original article he indicates the use of ten observations for both years.

(c) In essence, parts (a) and (b) tested for slope parameter stability *within* the first and the second generations of computers, respectively. To test whether the hedonic relationship changed *between* the first and second generations, it will be useful to run one additional regression covering the entire 1954–1965 time period, namely, a specification in which LNRENT is regressed on a constant, year-specific dummy variables for 1955 through 1965, LNMEM, LNMULT, and LNACCESS. Having run this regression, and initially assuming equality of the slope parameters within the first (1954–1959) and the second (1960–1965) generations, test the null hypothesis that the slope coefficients of the first generation equal those of the second generation. Does this result surprise you? Why or why not? Next, relax the assumption of slope parameter equality within each generation, and test the null hypothesis that slope parameters are equal over the entire 1954–1965 time span against the alternative hypothesis that these slope coefficients varied from year to year. Note that calculation of the appropriate F-statistic requires comparing the sums of squared residuals from the 12 separate year-by-year regressions with that from the pooled 1954–1965 regression and then adjusting by the appropriate degrees of freedom. Interpret your results. Are the two test results of part (c) mutually consistent? Why or why not?

(d) The above tests for parameter stability are in essence a variant of the well-known Chow test (yes, the same Gregory Chow who wrote the computer article), described in most econometrics textbooks. In order that this test statistic be valid, it is necessary to assume that disturbances are distributed independently among models and over time and, perhaps more important, that their variance is constant over time. Chow's estimates of the disturbance variance, denoted s^2, are reproduced in Table

4.1. Using any one of the tests for homoskedasticity described in your econometrics textbook, test whether the homoskedasticity assumption is valid within the two generations and between the two generations. What do your results imply concerning the validity of the tests performed in parts (a) through (c)?

EXERCISE 6: Using Time-Varying Hedonic Price Equations to Construct Chained Price Indexes for Computers

The procedures for constructing quality-adjusted price indexes for computers based on estimated hedonic price equations discussed in this chapter assumed that the slope coefficients were constant over time. In this exercise we relax the assumption of constant parameters over the entire data sample and instead employ adjacent year regression procedures to construct chained price indexes. The data used in this exercise are in the file named CHOW, within the subdirectory CHAP4.DAT, and are described at the beginning of Exercise 3.

(a) Consider the following regression equation, based on data from two adjacent years, for example, 1954 and 1955:

$$\begin{aligned}\mathrm{LNRENT}_{it} = \beta_0 + \beta_t\,\mathrm{DUM}_{it} + \beta_1\,\mathrm{LNMEM}_{it}\\ + \beta_2\,\mathrm{LNMULT}_{it} + \beta_3\,\mathrm{LNACCESS}_{it}\end{aligned}$$

where DUM_{it} is a dummy variable taking on the value of 1 if model i was introduced in the current year (say, 1955) and 0 if it was introduced in the adjacent previous year (1954). The estimate of β_t indicates the change in the natural logarithm of the price from 1954 to 1955, holding quality fixed. Such a regression equation could be specified for each pair of adjacent years, such as 1954–1955, 1955–1956, 1956–1957, . . . , 1964–1965. An attractive feature of the adjacent year regression approach is that the slope coefficients are allowed to vary over time. Using the data in the file CHOW, construct the appropriate variables, estimate the 11 adjacent year regression equations by ordinary least squares, and then retrieve the 11 estimates of β_t, denoted as β_{1955}, β_{1956}, β_{1957}, . . . , β_{1965}. Next, using data covering the entire 1954–1965 time period, estimate the more traditional hedonic regression equation in which LNRENT is regressed on a constant, 11 dummy variables D_{1955} to D_{1965}, LNMEM, LNMULT, and LNACCESS. Compare year-to-year *changes* in the estimated coefficients of these 11 dummy variables with the *levels* of the 11 β_t estimates. Why is it appropriate to compare year-to-year changes in the estimated dummy variable coefficients with levels of the estimated β_t? Comment on and interpret any differences that appear to be substantial.

(b) Calculate a traditional hedonic price index for computers over the 1954–1965 time period, normalized to unity in 1954, by simply exponentiating values of the estimated coefficients on the 11 dummy variables, D_{1955} to D_{1965}. Then construct a chained price index, using the following sequential procedure: For 1955, exponentiate β_{1955}; for 1956, exponentiate the sum $(\beta_{1955} + \beta_{1956})$; for 1957, exponentiate the sum $(\beta_{1955} + \beta_{1956} + \beta_{1957})$. Continue this for each year, until for 1965 the quality-adjusted price index is computed as the antilogarithm of the sum $(\beta_{1955} + \beta_{1956} + \beta_{1957} + \cdots + \beta_{1965})$. Why is such an index called a chained price index? Empirically compare this chained price index with the traditional hedonic price index. Do they differ in any substantial or systematic manner? Which index do you prefer, and why?

EXERCISE 7: Exploring Alternative Functional Forms for the Hedonic Price Equation Using Box-Cox Procedures

In Section 4.5 it was noted that the choice of a functional form for the hedonic price equation is often one made with a priori information having only limited influence, and goodness-of-fit criteria instead play a major role. The purpose of this exercise is to use the Box-Cox procedure to choose among alternative functional forms for the hedonic price equation. To do this exercise, you will need to have access to software programs that are capable of doing Box-Cox transformations.[46] The following nomenclature will be adopted: A Box-Cox transformation of the dependent variable involving a λ variable as in Eq. (4.12) will be called a λ_y transformation, while a Box-Cox transformation of the independent variables will be called a λ_x transformation. There are four common special cases of the Box-Cox transformation:

1. $\lambda_y = \lambda_x = 1$: a linear equation ($y$ on x),
2. $\lambda_y = \lambda_x = 0$: a log-log equation ($\ln y$ on $\ln x$),
3. $\lambda_y = 0, \lambda_x = 1$: a semilog equation ($\ln y$ on x), and
4. $\lambda_y = 1, \lambda_x = 0$: another semilog equation (y on $\ln x$).

It is important to note, however, that λ_y and λ_x can take on values other than 0 or 1. This implies that the Box-Cox procedure is not limited to the set of linear, log-log, and semilogarithmic functional forms.

For this exercise, choose and work through either part (a), dealing with the Waugh asparagus data, or part (b), based on the IBM study of disk drives. (Note: If you choose to work with the Waugh data, you will need to delete the 10 observations for which DISPERSE = 0.)

(a) Using the data on asparagus PRICE, GREEN, NOSTALKS, and DISPERSE in the data file WAUGH of the subdirectory CHAP4.DAT, estimate the four above special cases of the Box-Cox transformation, where in each case the same λ_x transformation is applied to each of the regressors GREEN, NOSTALKS, and DISPERSE. On the basis of the sample value of the log-likelihood function, which of these four functional forms is preferred? Now estimate the parameters λ_y and λ_x, where λ_x is still constrained to be the same for all three regressors but differs from λ_y. Are the estimated values of λ_y and λ_x close to any of the four special cases outlined above? Comment on the signs of the estimated coefficients and the implied shape of the hedonic price function. Using the likelihood ratio testing procedure, test each of these four special cases as a null hypothesis, where in each case the alternative hypothesis leaves λ_y and λ_x unconstrained. Finally, test the null hypothesis that $\lambda_y = \lambda_x$ against the alternative hypothesis that $\lambda_y \neq \lambda_x$.

(b) Data on PRICE, SPEED, and capacity (CAP) for hard disk drives in the United States over the 1972–1984 time period are found in the file COLE within the subdirectory CHAP4.DAT. Form a set of 11 dummy variables, $D_{73}, D_{74}, \ldots, D_{84}$, that take on the value of unity if the disk drive model was introduced in that particular year and is zero otherwise. In this exercise, Box-Cox transformations are performed on PRICE, SPEED, and CAP, but not on the intercept term or the dummy variables. Estimate the four above common special cases of the Box-Cox transformation, where in each case the same λ_x transformation is applied to each of the regressors SPEED and CAP. On the basis of the sample value of the log-likelihood function, which of these four functional forms is preferred? Does this result concur with that reported by Cole et al., discussed in Section 4.4? Now estimate separately the parameters λ_y and λ_x, where λ_x is still constrained to be the same for both slope regressors. Are the estimated values of λ_y and λ_x close to any of the four special cases outlined above? Comment on the signs of the estimated coefficients and the implied shape of the hedonic price function. Do values of the transformation parameters all lie in the 0–1 domain, or are some, as Triplett [1989] conjectured, in the negative domain? Using the likelihood ratio testing procedure, test each of these four special cases as a null hypothesis, where in each case the alternative hypothesis leaves λ_y and λ_x unconstrained. Then test the null hypothesis that $\lambda_y = \lambda_x$ against the alternative hypothesis that $\lambda_y \neq \lambda_x$. Finally, briefly outline how you would construct a price index series for disk drives based on your preferred functional form.

CHAPTER NOTES

1. A similar quote is attributed by Robert J. Gordon [1989, fn. 2] to the December 22, 1980 issue of *Forbes* magazine, which in turn attributes it to an unspecified issue of *Computerworld*.
2. For a discussion of such issues and appropriate references, see U.S. Department of Labor, Bureau of Labor Statistics [1982, Vol. II], Franklin M. Fisher and Karl Shell [1983], and Robert A. Pollak [1989].

3. See Rosanne Cole et al. [1986].
4. For a more detailed discussion of these issues, see Jack E. Triplett [1986] and the references cited therein.
5. See Rosanne Cole et al. [1986] and David W. Cartwright [1986].
6. Yet another approach also involves regression analysis but focuses on changes in the prices of characteristics.
7. This paper was part of Waugh's Ph.D. dissertation at Columbia University. It built on earlier work dating back to 1923 and was subsequently published as Frederick V. Waugh [1928].
8. Waugh [1928, p. 188].
9. Since Waugh [1929, p. 144] provides means for the dependent and independent variables, it is possible to work backwards and, using his parameter estimates for the slope coefficients and the fact that the least squares line always passes through the point of means, calculate the estimate of β_0. In this case this calculation turns out to be: $90.095 - 0.13826 \cdot 588.75 + 1.53394 \cdot 19.555 + 0.27553 \cdot 14.875 = 42.789$.
10. Waugh [1928, p. 189].
11. A discussion of partial and separate coefficients of determination is found in, among others, Arthur S. Goldberger [1964, pp. 197–200].
12. For a discussion of R^2 relationships in multivariate and multiple simple regression equations, see Arthur S. Goldberger [1968], especially Chapter 4.
13. This study was published in Andrew T. Court [1939].
14. It appears that the BLS price index was based primarily on data about the Ford Model T, a model that was relatively unchanged from year to year, and for which the matched model method worked quite well until the acceleration of technical change in the early 1930s.
15. Court [1939, p. 107].
16. If one exponentiates Eq. (4.6) and then takes expected values, the expected value of the exponentiated disturbance term is no longer zero but instead equals $0.5\sigma^2$; for discussion, see John Aitchison and James A. C. Brown [1966] or Dale M. Heien [1968]. An implication of the Aitchison-Brown result is that the estimate of $0.5\sigma^2$ should be added to each predicted price index before exponentiating Eq. (4.6). This adjustment is seldom done by empirical researchers, however, perhaps because it is typically quantitatively insignificant. Furthermore, if one is interested only in examining differences in predicted price indexes between years, for practical purposes this term will drop out.
17. Court [1939, p. 110].
18. Although a reduction in the growth rate of price indexes is common when one attempts to adjust for quality change, it is not always the case that price indexes based on hedonic regressions yield lower growth rates in times of technical progress than those obtained using traditional matched model techniques. For interesting counterexamples, see Meyer L. Burstein [1961] and Jack E. Triplett [1971].
19. See, for example, the interpretation of Court's findings by a GM official in Stephen M. Dubrul [1939].
20. See, for example, Hendrik S. Houthakker [1952], Richard Stone [1956], Jan Tinbergen [1956], and an obscure paper by William M. Gorman [1957].
21. See Zvi Griliches [1971] and Irma Adelman and Zvi Griliches [1961].
22. Some of this research in the 1961–1970 decade is summarized and referenced in Zvi Griliches [1971]. This volume also contains a number of other important papers commissioned by the Price Statistics Committee of the Federal Reserve Board. A more recent review is given in Griliches [1988, Part I].

23. It might be noted, however, that for about 20 years previously the BLS had used hedonic procedures to construct a new housing price index. In private correspondence, Jack Triplett has indicated that "the new house price index is a price index for characteristics—it is the ratio of current characteristics prices to those prevailing in 1982, weighted by the total quantities of characteristics sold."
24. Waugh [1929, p. 95].
25. For more detailed historical accounts, see, among others, Stan Augarten [1984]. Historical economic issues, particularly those involving mainframe computers and the International Business Machines Corporation, are discussed in Franklin M. Fisher, John J. McGowan, and Joen E. Greenwood [1983]. Also see Jack E. Triplett [1989] and Robert J. Gordon [1989].
26. On this, also see Cole et al. [1986].
27. A decimal digit counted as four binary digits, while an octal digit counted as three binary digits.
28. Table 4.1 corrects two typographical errors in Chow [1967, Table 1], namely, the signs on the estimated coefficients of the MEM and ACCESS variables in Chow [1967] are incorrect for the year 1961.
29. Chow [1967, pp. 1121–1122].
30. Chow reports that results were virtually identical when geometric means replaced the arithmetic means.
31. As of 1990, the official BEA price index for computers over the 1953–1969 is still constant; it is only from 1970 onward that it declines.
32. Also see Robert J. Gordon [1989].
33. Calculations were done under the assumption that the average amount of data transferred at one time is 2 kilobytes. Further, if multiple read/write heads appeared on a device, the speed of the device was measured as the speed per set times the number of sets.
34. The Cartwright deflator is in effect a Paasche price index with a moving reference year. For a deflator with fixed 1972 weights based on Laspeyres procedures, see Triplett [1989, Table 4.14, p. 196].
35. For further discussion, see your econometric theory textbook. A compact textbook treatment is given in George G. Judge et al. [1985, Chapter 20]. The original articles are George E. P. Box and David R. Cox [1964] and George E. P. Box and Paul W. Tidwell [1962]. Issues concerning estimation, inference, and computational algorithms are discussed by, among others, John J. Spitzer [1982, 1984].
36. In private correspondence, Ellen R. Dulberger has indicated that in her own research in Dulberger [1986] she employed Box-Cox transformations varying λ from 0 to 1 in increments of 0.1.
37. A related issue concerns the set of quality variables that should be included in the hedonic regression equation. Since alternative variables are often highly correlated with one another, parameter estimates frequently vary considerably with the choice of included variables. One possible procedure, used by Phoebus Dhrymes [1971] but little since then, employs factor analysis or principal components. Discussion of factor analytic methods, however, is also beyond the scope of this chapter; on this, see Harry H. Harman [1976].

38. For further discussion, see Fisher, McGowan, and Greenwood [1983]. It is worth noting that make effects might also capture manufacturer-specific pricing policies, such as failing to keep up with competitive price reductions.
39. See Dean F. Amel and Ernst R. Berndt [1986] and the references cited therein.
40. For an interesting application involving the effects of changes in gasoline prices on the valuations of fuel-efficiency characteristics of used automobiles, see Makoto Ohta and Zvi Griliches [1986].
41. See, for example, Robert E. Hall [1971] as well as the bibliographies at the end of Griliches [1971, 1988].
42. For a related application, see Franklin M. Fisher, Zvi Griliches, and Carl Kaysen [1962].
43. On this, see, for example, Fisher, McGowan, and Greenwood [1983] and Ellen R. Dulberger [1986].
44. The data are taken from Waugh [1929, Appendix, Table 1, pp. 127–131].
45. Your computed sample variances may be identical to those of Waugh, depending on whether your computer software computes sample variances by dividing the squared deviations around the mean by $n = 200$ or by $n - 1 = 199$.
46. Information on modifying conventional nonlinear least squares programs to perform Box-Cox estimation, as well as other computational issues, are discussed in John J. Spitzer [1982, 1984].

CHAPTER REFERENCES

Adelman, Irma and Zvi Griliches [1961], "On an Index of Quality Change," *Journal of the American Statistical Association*, 56:295, September, 535–548.

Aitchison, John and James A. C. Brown [1966], *The Lognormal Distribution*, Cambridge, England: Cambridge University Press.

Amel, Dean F. and Ernst R. Berndt [1986], "Depreciation in the Swedish Automobile Market: An Integration of Hedonic and Latent Variable Approaches," Cambridge, Mass.: Massachusetts Institute of Technology, Center for Energy Policy Research, Working Paper MIT EL 86-007WP, March.

Augarten, Stan [1984], *Bit by Bit: An Illustrated History of Computers*, New York: Ticknor & Fields.

Bartik, Timothy J. [1987], "The Estimation of Demand Parameters in Hedonic Price Models," *Journal of Political Economy*, 95:1, January, 81–88.

Box, George E. P. and David R. Cox [1964], "An Analysis of Transformations," *Journal of the Royal Statistical Society*, Series B, 26:2, April, 211–243.

Box, George E. P. and Paul W. Tidwell [1962], "Transformation of the Independent Variables," *Technometrics*, 4:4, November, 531–550.

Burstein, Meyer L. [1961], "Measurement of Quality Change in Consumer Durables," *The Manchester School of Economics and Social Studies*, 29:3, September, 267–279.

Cartwright, David W. [1986], "Improved Deflation of Purchases of Computers," *Survey of Current Business*, 66:3, March, 7–9.

Chow, Gregory C. [1967], "Technological Change and the Demand for Computers," *American Economic Review*, 57:5, December, 1117–1130.

Cole, Rosanne, Y.C. Chen, Joan A. Barquin-Stolleman, Ellen Dulberger, Nurhan Helvacian, and James H. Hodge [1986], "Quality-Adjusted Price Indexes for Computer Processors and Selected Peripheral Equipment," *Survey of Current Business*, 66:1, January, 41–50.

Court, Andrew T. [1939], "Hedonic Price Indexes with Automotive Examples," in *The Dynamics of Automobile Demand*, New York: The General Motors Corporation, 99–117.

Dhrymes, Phoebus J. [1971], "Price and Quality Changes in Consumer Capital Goods: An Empirical Study," Chapter 4 in Zvi Griliches, ed., *Price Indexes and Quality Change: Studies in New Methods of Measurement*, Cambridge, Mass.: Harvard University Press, 88–149.

Dubrul, Stephen M. [1939], "Significance of the Findings," *The Dynamics of Automobile Demand*, New York: The General Motors Corporation, 123–139.

Dulberger, Ellen R. [1986], *The Application of an Hedonic Model to a Quality Adjusted Price Index for Computer Processors*, unpublished Ph.D. dissertation, City University of New York, Department of Economics. Portions of this dissertation were published as "The Application of a Hedonic Model to a Quality-Adjusted Price Index for Computer Processors," Chapter 2 in Dale W. Jorgenson and Ralph Landau, eds., *Technology and Capital Formation*, Cambridge, Mass.: MIT Press, 1989, pp. 37–75.

Epple, Dennis [1987], "Hedonic Prices and Implicit Markets: Estimating Demand and Supply Functions for Differentiated Products," *Journal of Political Economy*, 95:1, January, 59–80.

Fisher, Franklin M. and Karl Shell [1983], *The Economic Theory of Price Indexes: Two Essays on the Effects of Taste, Quality and Technological Change*, Cambridge, Mass.: MIT Press.

Fisher, Franklin M., Zvi Griliches, and Carl Kaysen [1962], "The Costs of Automobile Model Changes since 1949," *Journal of Political Economy*, 70:5, October, 433–451.

Fisher, Franklin M., John J. McGowan, and Joen E. Greenwood [1983], *Folded, Spindled and Mutilated: Economic Analysis and U.S. vs. IBM*, Cambridge, Mass.: MIT Press.

Forester, Tom, ed. [1985], *The Information Technology Revolution*, Cambridge, Mass.: MIT Press.

Goldberger, Arthur S. [1964], *Econometric Theory*, New York: John Wiley and Sons.

Goldberger, Arthur S. [1968], *Topics in Regression Analysis*, New York: Macmillan.

Gordon, Robert J. [1989], "The Postwar Evolution of Computer Prices," Chapter 3 in Dale W. Jorgenson and Ralph Landau, eds., *Technology and Capital Formation*, Cambridge, Mass.: MIT Press, pp. 77–125.

Gorman, William M. [1957], "A Possible Procedure for Analyzing Quality Differentials in the Egg Market," Iowa Agricultural Experiment Station, Working Paper, revised, February. Reissued in January 1976 as Discussion Paper No. B4, London: London School of Economics.

Griliches, Zvi [1961], "Hedonic Price Indexes for Automobiles: An Econometric Analysis of Quality Change," in *The Price Statistics of the Federal Government*, General Series No. 73, New York: Columbia University Press for the National Bureau of Economic Research, pp. 137–196. Reprinted in Zvi Griliches, ed., *Price Indexes and Quality Change: Studies in New Methods of Measurement*, Cambridge, Mass.: Harvard University Press, 1971, pp. 55–87.

Griliches, Zvi [1971], "Introduction: Hedonic Price Indexes Revisited," in Zvi Griliches, ed., *Price Indexes and Quality Change: Studies in New Methods of Measurement*, Cambridge, Mass.: Harvard University Press, pp. 3–15.

Griliches, Zvi [1988], *Technology, Education, and Productivity*, New York: Basil Blackwell.

Hall, Robert E. [1971], "The Measurement of Quality Change from Vintage Price Data," Chapter 8 in Zvi Griliches, ed., *Price Indexes and Quality Change: Studies in New Methods of Measurement*, Cambridge, Mass.: Harvard University Press, pp. 240–271.

Hamilton, David [1987], "Sometimes $R^2 > r^2_{yx_1} + r^2_{yx_2}$: Correlated Variables Are Not Always Redundant," *American Statistician*, 41:2, May, 129–132.

Harman, Harry H. [1976], *Modern Factor Analysis*, Third Edition, Chicago: University of Chicago Press.

Heien, Dale M. [1968], "A Note on Log-Linear Regression," *Journal of the American Statistical Association*, 63:323, September, 1034–1038.

Houthakker, Hendrik S. [1952], "Compensated Changes in Quantities and Qualities Consumed," *Review of Economic Studies*, 19(3), 155–164.

Judge, George G., William E. Griffiths, R. Carter Hill, Helmut Lutkepohl, and Tsoung-Chao Lee [1985], *The Theory and Practice of Econometrics*, Second Edition, New York: John Wiley and Sons.

National Bureau of Economic Research [1961], *The Price Statistics of the Federal Government*, General Series No. 73, New York: Columbia University Press for the National Bureau of Economic Research.

Ohta, Makoto [1975], "Product Technologies of the U.S. Boiler and Turbo Generator Industries and Hedonic Price Indexes for Their Products: A Cost Function Approach," *Journal of Political Economy*, 83:1, February, 1–26.

Ohta, Makoto and Zvi Griliches [1986], "Automobile Prices and Quality: Did the Gasoline Price Increases Change Consumer Tastes in the U.S.?" *Journal of Business and Economic Statistics*, 4:2, April, 187–198.

Pollak, Robert A. [1989], *The Theory of the Cost-of-Living Index*, New York: Oxford University Press.

Rosen, Sherwin M. [1974], "Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition," *Journal of Political Economy*, 82:1, January/February, 34–55.

Spitzer, John J. [1982], "A Primer on Box-Cox Estimation," *Review of Economics and Statistics*, 64:2, May, 307–313.

Spitzer, John J. [1984], "Variance Estimates in Models with the Box-Cox Transformation: Implications for Estimation and Hypothesis Testing," *Review of Economics and Statistics*, 66:4, November, 645–652.

Stone, Richard [1956], *Quality and Price Indexes in National Accounts*, Paris: Organization for European Economic Cooperation.

Tinbergen, Jan [1956], "On the Theory of Income Distribution," *Weltwirtschaftliches Archiv*, 77, 155–175. Reprinted in L.H. Klaassen, L.M. Koyck, and H.J. Witteveen, eds., *Selected Papers of Jan Tinbergen*, Amsterdam: North-Holland, 1959, pp. 243–263.

Triplett, Jack E. [1971], "Quality Bias in Price Indexes and New Methods of Quality Measurement," Chapter 6 in Zvi Griliches, ed., *Price Indexes and Quality Change*, Cambridge, Mass.: Harvard University Press, pp. 180–214.

Triplett, Jack E. [1986], "The Economic Interpretation of Hedonic Methods," *Survey of Current Business*, 66:1, January, 36–40.

Triplett, Jack E. [1989], "Price and Technological Change in a Capital Good: A Survey of Research on Computers," Chapter 4 in Dale W. Jorgenson and Ralph Landau, eds., *Technology and Capital Formation*, Cambridge, Mass.: MIT Press, pp. 127–213.

U.S. Department of Labor, Bureau of Labor Statistics [1982], *BLS Handbook of Methods*, Vols. I and II, Washington, D.C.: U.S. Government Printing Office.

Watts, Harold W. [1965], "The Test-o-Gram: A Pedagogical and Presentational Device," *American Statistician*, 19:4, October, 25–28.

Waugh, Frederick V. [1928], "Quality Factors Influencing Vegetable Prices," *Journal of Farm Economics*, 10:2, April, 185–196.

Waugh, Frederick V. [1929], *Quality as a Determinant of Vegetable Prices: A Statistical Study of Quality Factors Influencing Vegetable Prices in the Boston Wholesale Market*, New York: Columbia University Press. Reprinted by the AMS Press, Inc., New York, 1968.

FURTHER READINGS

Gordon, Robert J. [1990], *The Measurement of Durable Goods Prices*, Chicago: University of Chicago Press. See especially Chapter 6, "Electronic Computers."

Griliches, Zvi, ed. [1971], *Price Indexes and Quality Change: Studies in New Methods of Measurement*, Cambridge, Mass.: Harvard University Press. A collection of classic articles.

Griliches, Zvi [1988], *Technology, Education, and Productivity*, New York: Basil Blackwell. See especially Part I, which updates the material in Griliches [1971].

Lancaster, Kelvin [1971], *Consumer Demand: A New Approach*, New York: Columbia University Press. A theoretical framework emphasizing the role of characteristics and attributes in demand analysis.

Stigler, Stephen M. [1986], *The History of Statistics: The Measurement of Uncertainty before 1900*, Cambridge, Mass.: Harvard University Press. An enjoyable historical account of statistical measurement issues.