By ALLAN H. YOUNG

BEA's Measurement of Computer Output

THIS article addresses issues raised in a recent study by Edward Denison about BEA's measurement of the output of computers.[1] Denison concludes that BEA's measurement of the output of computers in the national income and product accounts (NIPA's) is incorrect. He argues that BEA did not implement the resource-cost concept of capital in measuring the output of computers when it introduced the computer price index in the comprehensive revision of the NIPA's in 1985 and that, consequently, computers are not measured in terms of the concept used for other types of capital goods. He also suggests that consideration be given to measuring capital in terms of consumption forgone rather than in terms of resource cost.

Part I of this article, "Capital Measured by Cost," introduces three issues raised by Denison concerning whether BEA's measurement of the output of computers implemented the resource-cost concept, demonstrates that the approach BEA used is consistent with the resource-cost concept, and examines some aspects—largely statistical in nature—that one needs to consider in evaluating the approach.

Part II, "Capital Measured by Consumption Forgone," considers Denison's reason for advancing the consumption-forgone concept and notes related work by other investigators.

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1. Edward F. Denison, *Estimates of Productivity Change by Industry* (Washington, DC: The Brookings Institution, 1989).

Part III, "A Summing Up," reviews why Denison's study does not present convincing reasons to change the treatment of computers in the measurement of output and suggests that the consumption-forgone concept can play a useful role in studying sources of growth but not in measuring the output of capital goods.

The overall topic of Denison's study is the estimation of productivity. In addition to considering BEA's measurement of the output of computers, Denison raises two issues pertaining to BEA that are not addressed in this article. One pertains to possible errors in the way BEA partitions growth in GNP among industries. The other pertains to whether BEA's new computer price index lessens the usefulness of measures of GNP based on a single weight year. BEA addressed the first of these two issues in an article in the July 1988 SURVEY OF CURRENT BUSINESS.[2] That article also evaluated similar points raised by Lawrence Mishel.[3] An article in the April 1989 SURVEY considered aspects of the second issue; it described BEA's plans to develop alternative measures of real GNP that use different approaches to weighting components.[4] Other parts of Denison's study that pertain to the Bureau of Labor Statistics (BLS) calculation of estimates of multifactor productivity by industry and his suggestion that productivity by end product be calculated are not taken up here.[5]

2. "Gross National Product by Industry: Comments on Recent Criticisms," SURVEY OF CURRENT BUSINESS 68 (July 1988): 132-133.

3. Lawrence Mishel, *Manufacturing Numbers: How Inaccurate Statistics Conceal U.S. Industrial Decline* (Washington, DC: Economic Policy Institute, 1988).

4. Allan H. Young, "Alternative Measures of Real GNP," SURVEY OF CURRENT BUSINESS 69 (April 1989): 27-34.

5. BLS currently prepares multifactor productivity measures for three major sectors of the economy, twenty two-digit manufacturing industries, and four three-digit manufacturing industries. For the major sectors and the two-digit multifactor measures, BLS uses BEA output in the preparation of its output measures and incorporates BEA's measures of gross private domestic fixed investment in the calculation of capital services.

I. Capital Measured By Cost

Issues Raised by Denison

This section introduces three issues raised by Denison concerning whether BEA implemented the resource-cost concept in measuring the output of computers.

In his study, Denison reviews BEA's treatment of computers in light of the methods of measuring capital that he first advanced in his seminal paper on the measurement of capital in the mid-1950's. The following descriptions of these methods are from his 1989 study; the methods are described more fully in his original paper.

> *Method I: Capital measured by cost.* The first method is both fruitful and practical. The value, in base period prices, of the stock of durable capital goods (before allowance for capital consumption) measures the amount it would have cost in the base period to produce the *actual* stock of capital goods existing in the given year (*not* its equivalent in ability to contribute to production). Similarly, gross additions to the capital stock and capital consumption are valued in terms of base year costs for the *particular* types of capital goods added or consumed. For durable capital goods not produced in the base year, one must substitute the amount it would have cost to produce them if they had been known and actually produced. But a similar modification is required in all deflation or index number problems. . . .

Method 2: Capital input proportional to total output. This method, deriving from the assumption of constant capital-output ratios, assumes that the capital stock moves in proportion to output. It is essential to realize that the method does not yield a measure of capital's contribution to output. For use as such a measure, its result is fatally flawed because the method takes no account of other inputs. For example, if output doubles with a new machine, the new machine is said to be twice as much capital as the old, regardless of whether its operation requires one-tenth as much labor, structures, materials, or other inputs as the old machine or ten times as much. Because it does not take account of changes in requirements for other inputs, it is a nonsense method that I have not heard advocated for many years.

The new measures of quantities and prices of computers are based on the computer's capacity to acquire, store, retrieve, process, and display information. They take no account of requirements for other inputs-labor, electricity, structures, paper, programs, and so on—and therefore appear to correspond to method 2 measures.[15] . . .

15. I ignore here the consideration that even believers in the constant capital-output ratio have usually applied it to the total output and capital of an industry or the whole business sector, not to the output of a particular process and a particular machine used in that process.

Method 3: Capital measured by marginal products. This third method requires that not only the effect of a new machine on output but also the effect on requirements for other inputs be taken into account. New capital goods are equated with old ones by their marginal products. The input of a type of machine moves like its contribution to output. If the new good has a marginal product twice as large as the old, it represents twice as much capital. The ordinary capital-output ratio is free to move as it will, in contrast to method 2.[6]

Except for computers, Denison and BEA agree that method 1—capital measured by cost, which in this article is called the resource-cost concept—is used by BEA to measure both the output of capital in the NIPA's and the associated stocks of fixed capital. In the case of computers, BEA takes the position that its approach is consistent with method 1. Denison takes the position, however, that BEA's treatment of computers is not in accord with method 1 but with method 2. As Denison describes method 2, its key feature is that the estimator imposes proportionality between capital and output as a way of estimating capital.[7]

Denison also evaluates BEA's approach in terms of method I. He faults it because of "the introduction of new products (models) into the price index by comparing their prices and characteristics with older ones in the year they appear on the market."[8] Consequently, in Denison's view, BEA's computer price index declines too rapidly, thereby overstating the growth of capital and understating the contribution to growth made by advances in knowledge.

Also in terms of method 1, Denison faults BEA's approach because it extends "the values for performance characteristics far beyond the range attained by products previously available."[9]

How BEA Measures Computers

This section illustrates BEA's approach to measuring the output of computers in terms of hypothetical examples that are designed to show that the approach is consistent with the resource-cost concept.

The essence of BEA's treatment of computers may be viewed as composed of three procedures, designated A, B, and C. Procedure A measures the quantity and price of an identical machine that is produced over time with successive, improved technologies. Procedure B measures the quantity and price when a second machine, the same in type but different in size, is introduced in the base year. Procedure C measures the price of a hypothetical machine of a specified size using data on machines of other sizes. For each procedure, the example makes clear how observed prices are used to establish the resource cost of the machine in question. (The designation of A, B, and C does not reflect the order in which the procedures are applied, but only the order chosen to facilitate their description.)

Procedure A

Procedure A measures the quantity and price of an identical machine that is produced over time with successive, improved technologies. It is illustrated in exhibit 1. The exhibit is designed (1) to highlight several characteristics of computer production that must be taken into account in measuring prices and output and (2) to set the stage for the discussion of capital measured by consumption forgone in part II. Lines 1–15 in the exhibit illustrate procedure A; lines 16-26 pertain to part II.

The basis for the example.—The example incorporates the following conditions. Suppose that an identical machine is produced each year and that every 3 years a new technology is introduced that reduces the resources required to produce the machine. Each successive technology overlaps the previous technology by 1 year. In the year in which the two technologies coexist, the price of the machine produced with the new technology is set higher than the machine's cost of production, while the price of the machine produced with the old technology is set lower than the cost of production. In the second year of a new technology, the price of the machine is set equal to the cost of production. In the third, the price is set lower, reflecting the arrival of the next generation of technology. Further, for simplicity, in the year in which two technologies overlap, the example assumes that one-half of the machines are produced by the new technology and one-half by the old and that the premium and discount are such that the machines are equal in price. In addition, suppose that the price of resources required to produce the machine increases each year irrespective of the particular technology in place. Finally, year 2—a year in which the price of the machine is equal to the cost of production—is taken as the base year.

Lines 1–15 in exhibit 1.—In the exhibit, the successive technologies are

6. Denison, *Estimates,* pp. 25-28; and "Theoretical Aspects of Quality Change, Capital Consumption, and Net Capital Formation," in *Problems in Capital Formation,* Studies in Income and Wealth, Volume 19 (Princeton, NJ: Princeton University Press for the National Bureau of Economic Research, 1957), 215-261.

7. Distinctions between method 1 and method 3 are not taken up in this article. Denison has advocated method 1 for measuring both the output of capital goods and for measuring the stock of capital from which he derives capital services. Many investigators consider method 1 to be the appropriate concept for measuring the output of capital and method 3 to be the appropriate concept for capital services. Jack Triplett of BEA, among others, argues that in most practical cases method 3 and method 1 will give similar results because, for small changes and in equilibrium, an improved machine will be adopted whenever the value of its increased marginal product (over the old) exceeds the price premium charged for it and because the price differential, in equilibrium, will also approximate the ratio of marginal production costs for the two machines. See Jack E. Triplett, "Concepts of Quality in Input and Output Price Measures: A Resolution of the User Value-Resource Cost Debate," in Murray F. Foss, ed., The *U.S. National Income and Product Accounts: Selected Topics.* Studies in Income and Wealth. Volume 47 (Chicago: University of Chicago Press for the National Bureau of Economic Research., 1983)., 296–311.

8. Denison, *Estimates*, p. 29.

9. Denison, *Estimates,* p. 27.

designated I, II, and III. Lines 1–3 show the number of units of the machine that are produced with each technology. For each technology, one machine is produced in the first year, two in the second year, and one in the third year, when a newer technology is also in place. Lines 4-6 show the price of the machine dropping with each successive technology, with the prices of the machines produced by two overlapping technologies being equal. Lines 7–10 show the revenue realized from sale of the machines-the number of units times the price.

Lines 11–14 show the value of the machines in terms of production costs in the base year; that is, they implement Denison's method 1 for measuring capital in terms of its resource cost. The entries are obtained by multiplying the base-year (year 2) price of the machine times the number of machines produced each year. Given that the price is equal to production costs in year 2, this method values the machines in terms of resource costs in the base year. Line 15 shows the price index for the machine, computed by dividing the total constant-dollar value of the machines (line 14) into the current-dollar revenue (line 10).

The following points about the entries on lines 1–15 should be noted.

(1) Given the stipulation that the machines produced over time are identical, the example presents no obstacle to the conventional methods of measuring price change, such as those BLS uses to measure producer prices, which implement the resource-cost concept.

(2) Although the observed price of the machine does not equal the resource cost in each year, one can still measure the machines produced in terms of resource cost in the base year. To obtain the desired measure, the estimator must only either know or assume the relationship between price and resource cost in the base year. In the example, the two are taken to be equal.

(3) The designation of the measures on lines 11–14 is chosen so as to clarify one aspect of Denison's description of method 1: That the machines produced each year are valued in terms of the real resources required to produce them in the base year with *base-year technology.*

Lines 16–26 in exhibit 1.—The remainder of the exhibit introduces a second measure of real resource cost, which will be discussed in part II. In this measure, real resources are stated in terms of *current-year technology.* This measure is obtained by deflating the current-dollar resource cost by an index of resource (input) prices. Line 16 shows the resource price index, and lines 17–20 show the current-dollar resource costs. The entries for years 2, 4, and 6, when only one technology is in use, are equal to the current-dollar revenue entries on lines 7–10. The entries for the other years are calculated according to the assumed change in resource prices shown on line 16.

Lines 21–24 show the second measure of real resource cost—the real resources required to produce the machines with current-year technology. They are obtained by dividing the resource price index (line 16) into the resource cost in current dollars (lines 17–20).

The ratio of real resource cost expressed in terms of base-year technology to that expressed in terms of current-year technology measures the technological change in the production of the machine. For years 2, 4, and 6, the ratio of the resource price index to the machine price index likewise measures technological change. These ratios are shown as indexes of technological change on lines 25 and 26. (No entries are shown on line 26 for years 1, 3, 5, and 7, because in those years the price of the machine is not equal to its cost of production.)

Exhibit 1.—Identical Machines Produced With Successive Generations of Improved Technology

Line		Year						
		1	2	3	4	5	6	7
	Units produced (number):							
1	Technology I	1	2	1				
2	Technology II			1	2	1		
3	Technology III					1	2	1
	Price (dollars):							
4	Technology I	1.18	1.00	.85				
5	Technology 11			.85	.72	.61		
6	Technology III					.61	.52	.44
	Revenue (dollars):							
7	Technology I	1.18	2.00	.85				
8	Technology II			.85	1.44	.61		
9	Technology III					.61	1.04	.44
10	Total	1.18	2.00	1.70	1.44	1.22	1.04	.44
	Resource cost in constant (year 2) do liars with base- year (year 2) technology:							
11	Technology I	1.00	2.00	1.00				
12	Technology II			1.00	2.00	1.00		
13	Technology III					1.00	2.00	1.00
14	Total	1.00	2.00	2.00	2.00	2.00	2.00	1.00
15	Machine price index (year 2=1.00)	1.18	1.00	.85	.72	.61	.52	.44
16	Resource price index (year 2=1.00)	.95	1.00	1.05	1.10	1.16	1.22	1.28
	Resource cost in current dollars:							
17	Technology I	.95	2.00	1.05				
18	Technology II			.69	1.44	.76		
19	Technology III					.49	1.04	.55
20	Total	.95	2.00	1.74	1.44	1.25	1.04	.55
	Resource cost in constant (year 2) dollars with current-year technology; -							
21	Technology I	1.00	2.00	1.00				
22	Technology II			.66	1.31	.66		
23	Technology III					.43	.85	.43
24	Total	1.00	2.00	1.66	1.31	1.09	.85	.43
	Technological change index (year 2=1.00):							
25	Line 14/line 24	1.00	1.00	1.20	1.53	1.83	2.35	2.35
26	Line 16/line 15		1.00		1.53		2.35	

NOTE.—The example does not show technologies before I and after III. Entries for units produced and price in years 1 and 7 assume technological change is occurring in a similar manner before I and after III.

Procedure B

Procedure B provides the total constant-dollar resource cost when two or more machines of different sizes are produced in the base year. It is a type of procedure basic to all price index work. The procedure is illustrated in exhibit 2, where a standard size machine is produced in years 1, 2, and 3 and a large size version is produced in years 2 and 3. Year 2 is the base year, and in that year the price of each machine is equal to its cost of production. Under these conditions, the total constant-dollar resource cost in terms

Exhibit 2.—Two Machines of Different Sizes Produced in the Base Year

	Year		
	1	2	3
Units (number):			
Standard size	1	1	1
Large size		1	1
Price (dollars):			
Standard size	1.2	1.0	.8
Large size		1.5	1.3
Revenue (dollars):			
Standard size	1.2	1.0	.8
Large size		1.5	1.3
Total	1.2	2.5	2.1
Resource cost in constant (year 2) dollars with base-year (year 2) technology:			
Standard size	1.0	1.0	1.0
Large size		1.5	1.5
Total	1.0	2.5	2.5
Machine price index (year 2=1.00)	1.20	1.00	.84

of base-year technology is the sum of the cost for each machine.

Procedure C

So far, procedures have been set forth for incorporating into the price index the prices of identical machines produced with successive, improved technologies and the prices of machines of the same type, but of different size, produced in the same period. These two procedures would be sufficient for pricing computers if each size of machine were represented in the base year. Because this is not the case, it is necessary to establish for each size of machine that is not produced in the base year the price in the base year of a hypothetical machine with identical characteristics. Procedure C, which is an application of the hedonic technique, estimates this price from data on the prices and characteristics of actual machines in the base year. Once the necessary hypothetical machines are established in the base year (procedure C), each machine produced in years other than the base year can be related to either an actual or hypothetical identical machine in the base year (procedure A), and the various actual and hypothetical machines in the base year can be equated to each other (procedure B).

The application of the hedonic technique is illustrated in exhibit 3, in which the price of different sized goods is determined by only one variable. Suppose that a type of lathe is produced in several sizes, but that not all sizes are produced in any given year. Everything about the lathe—the motor, cutting tool, etc.—is the same for each size, except for the bed and the frame required to support the bed. Over time, the price of the lathe is reduced. These price reductions are made possible by developments pertaining to the cost of the bed and frame: Stronger, lighter, less expensive materials; new methods of fabricating and assembling; and improved design that reduces use of a given material, independent of other factors. (For simplicity, the selling price is assumed to equal the resource cost in each period.) An example that incorporates these conditions is shown in the top panel of the exhibit.

In the example, year 1 is taken as the base period. In that year, lathes with beds and frames of 12”, 36”, and 48” are produced; in year 2, lathes of 36”, 48”, and 60” that reflect cost savings with respect to the bed and frame are produced; in year 3, lathes of 24”, 48”, and 72” that reflect further cost savings are produced. Thus, it is necessary to estimate the cost of hypothetical lathes of 24”, 60”, and 72” in year 1.

The costs of the hypothetical lathes are estimated by first establishing the costs of the bed and frame for the hypothetical lathes and then combining those costs with the fixed costs for the motor, cutting tool, etc. In the example, the cost of the bed and frame is linearly related to their length. The hypothetical cost of the 24” lathe in year 1, therefore, may be established in a straightforward manner. However, to infer hypothetical costs for 60” and 72” lathes, it is necessary to extend the cost relationship beyond the range of observations in year 1. The extension is based on the assumption that, if larger beds and frames had been produced in year 1, their costs would have been linearly related to their length in the same manner as in years 2 and 3. The bottom panel of the exhibit shows in parentheses the estimated hypothetical costs and sales prices.

Extending the cost relationship in the base year well beyond the range of observations is an issue raised by Denison. Several aspects of the issue need to be considered. Whether the same functional form holds across all years, as does the linear relationship in the example, is an empirical question that can be tested statistically.

Whether larger machines could have been produced in the base year at the cost predicted by the function is a technical question to which the answer may vary by type of machine and by type of technology. However, it seems reasonable to conclude that there would be few instances in which a larger size of a capital good could have been built in the base year for less than the predicted cost. The more likely case is that subsequent technological developments removed barriers existing in the base year that would have made larger machines very costly. Thus, extending the cost relationship in the base year to obtain predicted costs and sales prices for large hypothetical sizes may understate the cost of larger sizes in the base year and thereby understate the price decline from the base period to the later period.

Finally, if judged necessary, one may be able to minimize the need to extend the cost relationship by selecting one base year rather than another. For example, if one specified the most recent year as the base year, it would probably not be necessary to extend the function to larger machines, although it might be necessary to extend it to more smaller machines.

Exhibit 3.—Resource Cost and Price of Lathes of Different (Actual and Hypothetical) Sizes

	Year		
	1	2	3
Actual sizes			
Cost of bed and frame:			
12”	1.00		
24”			0.75
36”	2.00	1.20	
48”	2.50	1.50	1.25
60”		1.80	
			1.75
Cost of motor, cutting tool, etc., for all sizes	2.00	2.00	2.00
Total resource cost (equals sales price):			
12”	3.00		
24”			2.75
36”	4.00	3.20	
48”	4.50	3.50	3.25
60”		3.80	
72”			3.75
Actual and hypothetical sizes [1]			
Cost of bed and frame:			
12”	1.00		
24”	(1.50)		.75
36”	2.00	1.20	
48”	2.50	1.50	1.25
60”	(3.00)	1.80	
72”	(3.50)		1.75
Cost of motor, cutting tool, etc., for all sizes	2.00	2.00	2.00
Total resource cost (equals sales price):			
12”	3.00		
24”	(3.50)		2.75
36”	4.00	3.20	
48”	4.50	3.50	3.25
60”	(5.00)	3.80	
72”	(5.50)		3.75

1. Resource costs and sales prices of hypothetical sizes are shown in parentheses.

Application of the hedonic technique to computers.—In applying the hedonic technique to computers, one cannot proceed in the simple manner outlined in exhibit 3 for the following reasons.

(1) Detailed component cost data corresponding to those in exhibit 3 are not available for computers. The only data that are available correspond to the total prices of the lathes in the exhibit.
(2) Computers are more complex than the one variable case in the exhibit. For example, in terms of the exhibit, suppose that the horsepower of the motor was not fixed across all lathe sizes, but that a more powerful motor was available as an option, which, depending on the use of the machine, some purchasers would choose while others would not.
(3) The sizes of computers do not necessarily remain fixed. For example, in terms of the exhibit, suppose that in year 3 the producer added 1 inch to the size of each model so that the new lathes were 25", 49", and 73".

The complexities listed above were handled in the following manner for computers.

(1) A continuous function was fitted to actual prices to obtain hypothetical prices.
(2) Additional explanatory variables were included to represent additional, cost-determining characteristics (such as the size of the motor), and fixed costs (such as those for the cutting tool) were included in the constant term.
(3) The continuous function permitted information on machines of new sizes to be included.

Statistical Considerations

This section briefly examines several important, largely statistical aspects of BEA's measurement of the output of computers that one needs to consider in evaluating the approach. The note accompanying this article provides more details about the approach; the statistical and conceptual aspects of the approach are taken up more fully in the references cited in the note.

Applying the hedonic function

Selection of the function.—The mathematical function used in the hedonic technique, the log-log function, was selected based on statistical tests. Other functions that were tested included the linear and semilogarithmic functions.

In the case of computers, the estimated coefficients in the log-log function provide approximate proportionality, at any point in time, between a computer's characteristics and its price. That is, if one computer has twice the speed and memory size of another, its price will be approximately twice as high. This empirical finding might be what led Denison to describe BEA's procedure as corresponding to method 2. However, his method 2 does not pertain to proportionality between the characteristics of a computer and its price; rather, it pertains to proportionality between the stock of computers and the output of computer-using industries. BEA has in no way imposed proportionality of this latter kind. BEA did not even impose the approximate proportionality between the computer's characteristics and its price noted above; such proportionality was an empirical outcome.

Extension beyond the observed range in the base year.—The log-log function was extended beyond the range of observations in 1982 to impute hypothetical base-year prices both for large computers produced after 1982 and for small computers produced before 1982. The question of whether these extensions are appropriate statistically was examined in several tests.

One test applied when the function was initially fit to data for 1972–84 tested whether single-year regressions could be pooled into a multiyear regression. The test showed that the same function fit the data for the entire 1972–84 period, suggesting that imputing outside the range of 1982 probably involves only a small error.

Another test carried out initially involved tracking the price of a computer of given speed and memory size across the years included in the sample. It was found that the rate of price decline for a specified size of computer closely matched that for the computer price index BEA adopted as a deflator.

Later, using data through 1987, the function was examined for evidence that it had changed over time. The test showed that the parameters for 1985–87 do not differ significantly from those for earlier years.

These tests show that the selected log-log function is stable and well behaved. They do not indicate that extension beyond the observed range in the base year overstated the price decline.[10]

Introduction of new models

Denison maintains that new models should not be introduced into the price index in the year they appear on the market, on the grounds that the subsequent rapid price declines that come with large-scale production will receive undue weight. This point only applies to a situation in which a price movement that is not representative of the universe receives undue weight. This can be a problem in cases where the sample of products that are priced is selected judgmentally, or where the sample is extremely small. It should not, however, be a problem in BEA's computer price index, which is based on prices for *all models* within the defined category of equipment. Each model represents only itself and is priced over the entire model cycle. Beginning with the year of introduction, the new model's price can then be weighted by the actual market share of the model. In this way, one achieves an exact correspondence between the price represented in the price index and the price and sales quantity represented in the transactions data.

Selection of a base year

In measuring prices and output, the selection of a base year necessarily involves judgment. For computer processors, the explicit assumption is that the price of a processor incorporating 64 kilobit technology in 1982 was equal to its production cost. Because this technology was in place for a considerable period of time both before and after 1982, this appears to be a reasonable assumption. Similar assumptions were made for the other types of com-

10. The various tests and their results are described by Ellen R. Dulberger, "The Application of a Hedonic Model to a Quality-Adjusted Price Index for Computer Processors," and Jack E. Triplett, "Price and Technological Change in a Capital Good: A Survey of Research on Computers," in Dale W. Jorgenson and Ralph Landau, eds., *Technology and Capital Formation,* (Cambridge, MA: The MIT Press, 1989), 37-76 and 127-214; and by Jack E. Triplett, "Two Views on Computer Prices and Productivity," Bureau of Economic Analysis (Unpublished, 1989).

puter equipment. There is no apparent reason to conclude that the assumption that prices of the various types of equipment are equal to resource costs in 1982 introduced much error or that it was less appropriate for computers than for other capital goods.

Costless quality change

Costless quality change can be defined as the difference between (1) the value of a change in a good's ability to produce as a result of the addition of a new feature and (2) the cost of the new feature. Fundamentally, the difference between Denison's and BEA's approach lies in Denison's willingness to view an increase in memory size or speed as a new feature and then to assign it a zero cost. In BEA's approach, an increase in memory size or speed represents a resource cost and, through the use of the hedonic technique, it is treated as such and counted as part of measured quality—that is, as quantity. The difference between Denison and BEA is best considered not in terms of costless quality change, but in terms of how to measure resource cost accurately.

It should be noted that BEA's treatment of computers may not have filly accounted for the resource-using type of quality change. To the extent that computer manufacturers added features that had a cost in resources and that are not taken into account in the hedonic function, the estimated quality change falls short of the actual amount. For example, if in some year computer manufacturers introduced increased reliability at a resource cost, BEA would not have counted it as an increase in resource cost. Instead, such a cost would have been (incorrectly) counted as an increase in price. Given the possibility of situations such as this, BEA's computer price index may have understated the decline in computer prices.

Note on the Application of the Hedonic Technique

The application of the hedonic technique to develop a price index for computers and its use in deflating components of GNP was described in three articles by IBM staff and BEA staff in the SURVEY OF CURRENT BUSINESS in 1986.[1] In addition, an update on the use of the computer price index in deflating components of GNP was provided in an article in the November 1988 issue of the SURVEY.[2] Three topics covered in those articles will be taken up briefly: (1) The types of products for which price indexes were calculated, (2) the data on prices and characteristics, and (3) the measures of technology included in the hedonic function.

Price indexes were calculated for four types of computer equipment: Computer processors, disk drives, printers, and general purpose displays. The data on prices and characteristics were from publicly available sources and generally covered the period 1972-84. The sample for processors consisted of 67 different models from 4 manufacturers; that for disk drives, 30 devices marketed by 10 vendors; that for printers, 480 models marketed by 126 vendors; and that for displays, 772 models marketed by 115 vendors. Results obtained by the IBM staff from the processor sample were subsequently compared by BEA with results from an augmented sample containing 187 models from 17 manufacturers.

The selection of relevant characteristics was carried out by the IBM staff, drawing upon the expertise of both engineers and economists. For processors, two characteristics were selected-main memory capacity and a summary of speed at which instructions are executed. For disk drives, two characteristics were selected-capacity and speed.[3] For printers, three characteristics were selected—speed, resolution, and on-line fonts. For displays, four characteristics were selected—screen capacity, resolution, number of colors, and number of programmable function keys.

Technology was represented explicitly in the hedonic functions estimated for processors, disk drives, and printers. For processors, the sample was stratified into eight technology classes, ranging from magnetic core in 1972 to the 64-kilobit chip during 1979-84. For disk drives, nine technology classes were distinguished, having recording densities ranging from 220 kilobits per square inch in 1972 to over 12,000 kilobits per square inch during 1981–84. Printers were sorted into two categories—impact and nonimpact—and further classified by print mechanism. The function for displays did not account for technology, as distinguished from time.

1. Jack E. Triplett, "The Economic Interpretation of Hedonic Methods," and Rosanne Cole et al., "Quality-Adjusted Price Indexes for Computer Processors and Selected Peripheral Equipment," SURVEY OF CURRENT BUSINESS 66 (January 1986): 36-40 and 41-50; and David W. Cartwright, "Improved Deflation of Purchases of Computers," SURVEY OF CURRENT BUSINESS 66 (March 1986): 7-9.

2. David W. Cartwright, "Deflators for Purchases of Computers in GNP: Revised and Extended Estimates, 1983-88," SURVEY OF CURRENT BUSINESS 68 (November 1988): 22-23.

3. See Cole et al., p. 42, for the three components of disk drive speed.

Table 1.—Four Types of Computer Equipment, Average Annual Rates of Change in Composite Price Indexes

[Percent]

	Processors	Disk drives	Printers	Displays
1972-77	-11	–15	-6	–4
1977-84	-22	-11	-19	-l0
1972-84	–18	-13	-14	-7

A composite Paasche price index was constructed for each of the four types of equipment, using matched model prices wherever possible. When a model was not available in the base year (1982), an estimate of its price was made by valuing its characteristics produced with the dominant technology in 1982 using the estimated hedonic function. For processors, the dominant technology in 1982 was the 64-kilobit memory chip; for disk drives, it was recording densities of 3,071–3,084 kilobits per square inch. For printers, the estimate was made according to category and print mechanism. For displays, where technology did not appear explicitly in the function, estimates of unobserved prices were made by evaluating the function for implied prices of those characteristics in 1982.

The weights for the composite indexes for processors were estimates of the quantity of each model shipped; for disk drives, they were estimates of quantity shipped by technology class; and for printers, they were estimates of the quantity shipped by type of printer (e.g., dot matrix or laser jet). For displays, an equally weighted index was constructed. Except for processors, for which the shipments were available by model, the prices for models within a class were averaged to obtain an estimated price for the class.

The composite indexes showed substantial rates of price decline. The average annual rates of change for 1972–77, 1977–84, and 1972–84 are shown in table 1. Over the entire period 1972-84, the decline was largest for processors, at 18 percent per year; the decline was smallest for displays, at 7 percent per year. The composite indexes, along with a price index for tape drives, were combined into a deflator for computers and computing equipment using domestic shipments by type of equipment as weights. The deflator was extended back to 1969 using other information on computer prices. Prior to 1969, the deflator was held constant at the 1969 level.

The deflator was used in the deflation of components of GNP, as described in the previously referenced 1986 SURVEY articles. In July 1987, a separate index for personal computers (based on matched models) was introduced, as described in the November 1988 SURVEY article.

II. Capital Measured by Consumption Forgone

In his study, Denison advances a fourth method for measuring fixed capital stocks (and capital input) for the purpose of analyzing the sources of long-term growth. This method, which he designates method 4, would measure capital in terms of the consumption that is forgone in order to release resources for the production of capital goods. Denison defines net real investment in terms of consumption forgone as equal to "the quantity of consumer goods that resources devoted to increasing the capital stock would have provided if devoted instead to the production of consumer goods by the methods used in the base year."[11] Apparently, Denison favors measuring the output of capital goods as well as capital input in this manner.[12]

Denison advances method 4 in order to assign the contribution to growth that arises from productivity gains in the capital-goods-producing industries to the appropriate category in his growth accounting. When capital is measured by base-year resource cost and when output is measured net of depreciation, such gains are ultimately counted in capital's contribution to growth. By use of the consumption-forgone concept, Denison intends for such gains not to be counted in capital's contribution, but to be included in the residual—i.e., as gains not attributable to labor or capital—and counted as part of the contribution to growth of advances in knowledge.

Exhibit 1 illustrates a key feature of Denison's definition of capital measured in terms of consumption forgone. The phrase "resources devoted to increasing the capital stock" refers to the resources actually used in a given year in the production of capital. In terms of exhibit 1, these are the resources measured in terms of current-year technology on line 24. For example, in year 4 in the exhibit, the real resource cost (in year 2 dollars) to produce two machines is $1.31. If these resources had been "devoted instead to the production of consumer goods by the methods used in the base year," the cost (in year 2 dollars) of the consumer goods produced in year 4 would also have been $1.31. Thus, the difference between capital measured by method 1 and by method 4 is reflected in the index of technological change on line 25. If technological change permits a machine to be produced over time at a lower resource cost, it is counted as a decreasing amount of capital by method 4, while it is counted as a constant amount of capital by method 1.

In the exhibit, the entries for the price of inputs and the price of output were selected to correspond roughly to those for computers. The rate of technological change as represented by the index on line 25 is about 20 percent per year. Thus, the difference between Denison's method 1 and method 4 in the case of computers is substantial. The differences for other types of capital goods would be smaller.[13]

Work by other investigators

Denison cites the work by T.K. Rymes as the basis for his suggestion that capital be measured in terms of consumption forgone.[14] In his approach to productivity measurement, Rymes treats capital input as an intermediate good—as a produced means of production—and restates it so that it reflects the increasing efficiency with which it is produced. He shows that with the most aggregated approach, a restated measure of capital could be derived from data used in a conventional multifactor productivity calculation by subtracting from the change in capital either the difference between the change in the wage rate and the change in the price of output or the difference between the change in output and the change in labor input. However, a more detailed approach by industry is preferred; such an approach requires use of an input-output table to trace the effects of a productivity change in a given industry on other industries.

Recently, René Durand and Mehrzad Salem have argued that the timing of Rymes' restatement of capital input is incorrect.[15] According to Durand and Salem, Rymes restates capital in terms of the efficiency with which new capital is being produced in the current period. They argue that the restatement should be in terms of the periods in which the stock of capital in the current period was produced.

Charles Hulten also treats capital as an intermediate good in considering sources of growth.[16] He says "part of the historically observed growth rate of capital stock is . . . the *result* of productivity change, and must be recognized as such when assessing the importance of productivity change as a source of growth."[17] Hulten takes into account the increasing efficiency with which capital is produced with a two-stage approach. The first stage is a conventional multifactor productivity calculation. The second stage calculates a "dynamic residual" from the residuals in the conventional multifactor productivity calculation. This "dynamic residual" takes into account the expansion of capital induced by technological change.

Clearly, whether capital input should be measured in terms of consumption forgone instead of in terms of resource cost is far from settled. There may not even be agreement on how to implement the consumption-forgone concept. While Denison apparently favors measuring the output of capital as consumption forgone, the other investigators who advocate treating capital as an intermediate good apparently do not take this position. In fact, a theme in the work by Rymes is that capital should be stated differently as output in the numerator than as input in the denominator of a productivity ratio: Only the denominator would be restated to reflect the efficiency with which capital is produced.

As a data producer, BEA might at some point provide measures of capital stock in terms of consumption forgone, as an alternative to those in terms of resource cost. However, for the time being it would seem to be appropriate for any such restatements of capital input to be carried out by the productivity analyst.

11. Denison, *Estimates,* p. *30,* footnote *19.*

12. Denison, *Estimates,* pp. *36-37.*

13. The example assumes that the industry producing the computer also produces the inputs, such as semiconductors, that are also characterized by very rapid technological change.

14. T.K. Rymes, "The Measurement of Capital and Total Factor Productivity in the Context of the Cambridge Theory of Capital," *Review of Income and Wealth* 18 (March 1972): 79-108; and "More on the Measurement of Total Factor Productivity," *Review of Income and Wealth 29* (September 1983): 297–316.

15. René Durand and Mehrzad Salem, "Alternative Measures of Productivity Growth in a Rectangular Input-Output Framework," Statistics Canada (Unpublished, May 1989).

16. Charles Hulten, "On the Importance of Productivity Change," *American Economic Review 69* (March 1979): 126-136.

17. Ibid., 126.

III. A Summing Up

The computer represents a rate of technological change that, compared with the past, is unusual and that, more importantly, has not previously been faced fully either by the GNP estimator or by the productivity analyst. It is not surprising that BEA's introduction of the computer price index in 1985 has led to further examination of how the output of capital goods and capital input should be measured. No doubt there is more to be learned.

This article has demonstrated that BEA's approach to measuring the output of computers is consistent with the resource-cost concept of capital. BEA's approach may be viewed as consisting of three procedures, in each of which the observed prices are used to establish the resource cost of the computer in question. Fundamental to the approach is the definition of identical machines in procedure A. In that procedure, a new computer model is taken to be identical to an earlier computer model produced with less advanced technology if the two computers are identical in terms of cost-determining characteristics such as computation speed and memory size.

Given that observed prices are used to establish resource cost, there is no basis for Denison's conclusion that BEA implemented his method 2 rather than method 1. With respect to Denison's point that new models are introduced into the price index too early, it has been argued that BEA used the correct approach given that the price index is based on all models within the defined category, not on a judgmentally selected sample. With respect to Denison's point that it is not appropriate to extend the hedonic function beyond the observed range in the base year, statistical tests provide no evidence that the extension has overstated the price decline of computers. It has also been noted that the effect of omitting new features in the hedonic function would be to understate the price decline.

Finally, the restatement of capital input so that it reflects the increasing efficiency with which it is produced—the consumption-forgone concept favored by Denison—has appeal. Without such restatement, advances in knowledge may be assigned too small a role when considering sources of growth. Such a restatement can be carried out in the course of measuring capital input and its contribution to growth. With respect to the measurement of the *output* of capital goods, there appears to be little reason to replace the resource-cost concept with the consumption-forgone concept.