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REPLY: THE CONCEPT OF CAPITAL

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Edward Denison and I agree that the correct theoretical concept of capital is to consider two capital goods equivalent if they generate the same real net revenue, defined as gross revenue minus variable operating costs measured at a fixed set of output and input prices. Although I showed in my book that the correct concept could be fully implemented for commercial aircraft and electric generating equipment, for other products I was able only partially to take operating costs into account. As a result, both Denison and I agree that my radical revision to the official capital goods deflators does not go far enough and is biased toward understating improvements in quality. Our disagreement comes down to research strategy: I believe that I have progressed partway toward the ultimate goal of implementing the correct concept, while he views such a full implementation as infeasible. As a result, he advocates a return to the traditional criterion of base-period production cost, even though this yields price deflators that ignore improvements in performance (as for computers) and improvements in operating efficiency (as for successive generations of jet aircraft) made possible by technological advances that reduct the cost of production.

INTRODUCTION

Edward F. Denison was a great economist. Following on Robert Solow's 1957 demonstration that one could proxy the elasticity of output to changes in an input by that input's income share (assuming competitive factor pricing and constant returns to scale), Denison went on to invent and develop the field of growth accounting. Many of the basic innovations in this field were his, especially the treatment of labor input as human capital, the use of incomes stratified by educational attainment to obtain a measure of labor quality, and the recognition that some of these income differences reflect innate ability rather than the contribution of education.[1]

Perhaps the most contentious issue in the field of growth accounting has been the concept of capital input, and especially the allocation of the fruits of technical advance between the contribution of capital and the residual factor that Denison variously called "advances in knowledge," "residual productivity," or "output per unit of input." Thus it is fitting that Denison's last published article is devoted to an insightful and probing analysis of the concept of capital, taking as his point of departure my recent book, *The Measurement of Durable*

Note: This research has been supported by the National Science Foundation. This paper benefitted greatly from an exchange of correspondence with Edward Denison in late 1991.

[1]Most of his seminal innovations in growth accounting were introduced in his first (1962) book on the topic, which remains a landmark in the study of economic growth. I first read his book in an Oxford tutorial in 1962, an experience that played a major role in redirecting my main interest in economics from its previous focus on industrial organization to its subsequent focus on macroeconomics, economic growth, and the measurement of capital.

Goods Prices. I am honored that my book served as a catalyst for his final thoughts on capital measurement.

Points of Agreement and Disagreement

My book was the first to advocate a criterion for comparing capital goods based on their ability to produce real net revenue, defined as gross output minus variable costs spent on labor, energy, and other intermediate inputs. One chapter was devoted to an analysis of this concept and its relation to other approaches, including Denison's earlier writing, and the rest of the book attempted to implement the theoretical approach by providing quantitative estimates of quality and price changes for a wide variety of durable goods. Data were available to implement the theory completely for just two products, commercial aircraft and electric generating equipment. Estimates were produced for a wide variety of other products, including computers, automobiles, and appliances, where data allowed only a partial implementation of the theoretical formulation.

When aggregated into a new price deflator for producers' durable equipment, the book concluded that the official deflator had overstated price changes at a rate of about three percent per annum over the interval 1947–83, and that the growth of real equipment investment had been understated at the same rate. I argued that, although this estimate of price index bias may have seemed large, it was doubtless an understatement, and I ended my introductory chapter by listing 23 separate examples of unmeasured quality change that had not been taken into account in the estimates of the book.

Despite the appearance of major disagreement, Denison's paper endorses the two most important contributions of the book, the theoretical approach that compares capital goods by the net revenue criterion, and the empirical result that my new price deflators rise much less rapidly than the official deflators and doubtless understate the extent of the bias. On theory, he views my study as the first to apply the criterion of comparing capital goods by the marginal products "defined correctly," that is, by deducting operating costs. He views my approach not as a minor extension of previous analyses but as differing in a "major and fundamental way."[2] On empirical implementation, he emphasizes that I fail to adjust completely for operating cost on products other than aircraft and electric generating equipment, and so my estimates for other products understate the importance of quality change. In short, Denison concludes more forcefully than I did that the estimates of price index bias are understated, probably by a large amount.

Where, then, do we disagree? Denison concludes that my empirical work goes only part of the way toward a complete implementation of the net revenue criterion that both he and I endorse, that is, I have baked only "half a loaf." He believes that half a loaf is worse than none, while I think that half a loaf is better than none and is a good start toward everyone's objective of a "full loaf." As this analogy suggests, our ultimate disagreement concerns research strategy and is largely subjective.

[2] "... doing so is not *extending* the definition of marginal product but *implementing* it. Nor is the 'extension' slight; it is major and fundamental" (p. 92).

A Formal Analysis of Alternative Concepts of Capital

Denison's paper is complex and may be hard to follow for readers who are unfamiliar with his previous classifications of measures of capital by methods "1," "2," and "3." Here I provide a bare-bones formalization of the central distinctions in order to clarify both his position and mine.[3]

The economy produces output (y) with the characteristics of capital goods (x), e.g., computer calculations (MIPS) or trucking ton-miles, as well as variable inputs (q) like computer operators, truck drivers, and fuel. Here it is important that the measure of capital which enters the production function is the attribute of capital that actually produces output, e.g., computer calculations, not the particular unit in which a piece of capital is packaged (the computer "box"):

$$y = y(x, q), \qquad y_x > 0; \qquad y_q > 0. \tag{1}$$

The real net revenue generated from production is output minus the real cost of variable inputs, which in turn is equal to the real price of these inputs (w) times their quantity:

$$n = y(x, q) - wq(x, \sigma), \tag{2}$$

where the demand for inputs depends on the quantity of capital used and a technological shift parameter that can alter the requirements for variable inputs, e.g., as the result of fuel-saving technological change.[4]

The cost (v) of producing a capital good at any given time depends on its physical attributes (z), which in turn depend on the net revenue it can generate, as well as on a shift parameter that can change net revenue relative to physical attributes:[5]

$$v = v[z(n), \lambda], \qquad v_z > 0; \qquad v_\lambda < 0; \qquad z_n > 0. \tag{3}$$

This distinction between the physical attributes that determine cost (z) and net revenue (n) applies with most force in the computer industry. At any given moment of time computers generating more n (faster speed, greater memory) cost more to purchase in the marketplace, but a continuous increase in λ over time has allowed firms to increase n by many orders of magnitude without any appreciable increase in the price of a computer "box". The same goes for fuel economy; at any given moment of time more fuel-efficient models that generate higher n cost more to produce, but technological progress can improve the fuel economy of models of a given cost.

[3]What follows is a stripped-down version of the analysis on my book (1990, Chapter 2). The notation in the book has been retained where possible, although the emphasis here has been changed to focus on the concerns raised by Denison. The most important simplification is to eliminate a number of terms that allow the demand for characteristics of capital goods to respond to changes in the relative prices of output and inputs.

[4]Real net revenue in (2) is nominal net revenue divided by the price of output (P). Nominal net revenue is:

$$N = Py(x, q) - Wq(x, \sigma).$$

[5]In this analysis there is no distinction between the cost of a capital good and its market price; hence v represents both cost and price.

The Correct Measure of Capital and its Validation by Used Asset Prices

The debate over alternative methods of measuring capital involves the choice of alternative price deflators. We observe a given stream of investment on capital goods of various types measured in nominal dollars, and we need a deflator to convert this stream into constant dollars. The approach proposed in my book is to consider two goods as representing the same amount of capital if they yield the same net revenue at a given set of prices (w) of variable inputs. The implied deflator compares "model 1" with "model 0" at a given time, dividing their market price ratio by the ratio of the net revenue that they can generate:

$$(4) \qquad P^3 = \frac{v_1/v_0}{n_1/n_0} = \frac{v[z(n_1), \lambda_1]/v[z(n_0), \lambda_0]}{[y(x_1, q_1) - w_0 q(x_1, \sigma_1)]/[y(x_0, q_0) - w_0 q(x_0, \sigma_0)]}.$$

This price deflator is labelled P^3 because it is what Denison calls a correct implemention of his "method 3" of measuring capital. Note that in comparing the two models, the price of output and the real price of variable inputs (w_0) is held constant.

Several examples can be provided to illustrate the versatility of this concept. If the market price of a new model is double that of an old model, yet they produce the same real net revenue, the price deflator doubles. If the market price doubles but net revenue rises by a factor of 2, the price deflator is unchanged; this would be a typical event when a larger model replaces a smaller model without any shift in the cost of production parameter (λ) or in the efficiency of use of variable inputs (σ). When the first generation of jet planes was introduced, market price doubled, while net revenue increased by a factor of 10 as a result of both faster speed and reduced fuel use, so that the price index declined from 1.0 to 0.2.

As shown by the theoretical analysis in my book, the market for used assets should establish used prices (a) of two models of a given age in proportion to their ability to generate net revenue:

$$(5) \qquad \frac{a_1}{a_0} = \frac{n_1}{n_0}.$$

This relationship is important both theoretically and in empirical implementation. In theory it shows why net revenue rather than gross marginal product is the correct criterion for comparing capital goods. For instance, jet aircraft with similar speeds and seating capacities (e.g., the Boeing 757 and McDonnell-Douglas DC8-61) have very different prices on the used aircraft market (corrected for age) because the latter model uses more pilots and consumes much more fuel. In empirical implementation the availability of used asset prices provides data that can be used directly to compare models or to double-check computations of net revenue by model.

The Other Methods for Measuring Capital

Much of Denison's paper involves the contrast between "method 1," "modified method 1," and "method 3." Originally "method 1" considered two

capital goods to be equivalent if they had the same production cost in a particular base year. Making the same comparison between "model 1" and "model 0," and treating year "0" as the base year, the original method 1 deflator would be:

$$P^1 = \frac{v_1/v_0}{c_1/c_0} = \frac{v[z(n_1), \lambda_1]/v[z(n_0), \lambda_0]}{v[z(n_1), \lambda_0]/v[z(n_0), \lambda_0]}. \tag{6}$$

Notice that here the numerator is the same as in (4), but the denominator is the ratio of the cost of the new and old model at the base-period level of production technology (λ_0), that is, ignoring any changes in λ that make it possible to boost the productive characteristics of a machine of given base-period cost or to reduce the cost of obtaining improved fuel efficiency.

An intermediate step between methods 1 and 3 (introduced in Triplett's 1983 paper) is a reformulation of method 1 to consider as equivalent two capital goods that have the same productive characteristics (x), while continuing to ignore any differences in operating efficiency.

$$P^{1*} = \frac{v_1/v_0}{m_1/m_0} = \frac{v[z(n_1), \lambda_1]/v[z(n_0), \lambda_0]}{y(x_1)/y(x_0)}. \tag{7}$$

Again, the numerator is the same as before, but now the denominator is the ratio of the gross output that can be produced with the new and old models, neglecting any role for variable inputs (hence the terms in q in the denominator of 4 are omitted in 7). In most of his description, Denison intends this formulation to apply to hedonic price indexes for computers, in which the ratio of output produced by two computer models is determined by the ratio of their prices at a given time, ignoring any other input that is used cooperatively with computers.

"Method 2" is to consider two capital goods as equivalent if they produce the same output. Denison rightly dismisses this as eliminating the distinction between output and capital. Note that method 1* would be equivalent to method 2 only if the elasticity of output with respect to an increase in characteristics is unity.[6] What Denison elsewhere calls "method 4" is to measure capital as consumption foregone, i.e., apply the price deflator for consumption goods rather than to attempt to compute a separate price deflator for investment goods. We return to this suggestion below.

Problems of Implementing the Correct Capital Measure

The preferred "method 3" is implemented in my book for commercial aircraft and electric generating plants. Both of these have the great advantage of separable technology, so that the output, net revenue, and market price of each unit of capital can be measured separately. In the case of aircraft, net revenue for pairs of models was calculated and then roughly confirmed by ratios on the used aircraft market. Price indexes based on the net revenue and used asset ratios behaved similarly and differed radically from conventional indexes based on a "method 1" approach.

[6]Denison is not entirely consistent in his terminology. In the first part of his paper he refers to the reformulation of method 1 by Triplett in characteristics space as "reformulated method 1." But then he refers to the use by the BEA of a hedonic price index for computers as "modified method 2."

The analysis of aircraft prices reveals that there are good reasons why asset prices can differ (other than age) that are hard to measure in comparisons of net revenue. If model "1" produces an output of higher quality than model "0" (e.g., less vibration for a jet plane than for a piston plane), but the market for this product (airline travel) is such that no price differential exists between the product of the old and new model (the benefit being passed on to the consumer), then the net revenue method will "miss" the improvement in this quality attribute. However, the used asset price will capture the improvement, since the bids by potential equipment purchasers will reflect their knowledge that consumers prefer the new model. Also, the used price method is superior, since used prices incorporate current expectations about useful lifetimes.

Once we go beyond the aircraft and electric utility chapters, the empirical implementation in the book does not make explicit calculations of net revenue for other products. For such products as appliances and TV sets, rough adjustments are made for the value of reduced energy use and repair frequency, and data on the prices of used automobiles and tractors are also employed. The bias to which Denison calls attention applies to any price comparison, especially by the hedonic method, which ignores operating costs.

Denison's criticism applies with particular force to computers, where I find that between 1951 and 1984 the computer price index fell by a factor of 1,337. Since the nominal price of computers changed little, the implied quality of computers measured by method 1* increased by a factor of 1,337. Denison dramatizes his criticism by arguing that I implicitly assumed that a 1984 computer processor "required 1,337 times as much labor to operate it. Requirements for structures, inventories, land, and purchased materials and services are also assumed to be 1,337 times as great in 1984 as in 1951." In truth, 1984 computers doubtless required less of most types of variable inputs than 1951 computers, not more. Denison's criticism applies to all hedonic regression studies of high-tech products, not just those in my book.

The bias that Denison identifies goes unambiguously in the direction of causing my price indexes to understate quality improvements by a significant amount. Denison provides no guidance on the size of the bias, but it is easy to work out a formal assessment. We want a price index that divides the price ratio of a new and old model by their net revenue ratios, as in (4). Yet the hedonic regression methodology makes the mistake of comparing the gross marginal products, i.e., compares two models by $y(x_1)/y(x_0)$ instead of n_1/n_0. To simplify, let us assume that a new model of, say, a computer has more computation power (a higher x) but uses an unchanged quantity of labor, electricity, and other input characteristics. Then the net revenue ratio from (4) is:

$$\frac{n_1}{n_0} = \frac{y(x_1) - w_0 q_0}{y(x_0) - w_0 q_0}. \tag{8}$$

Dividing through by $y(x_1)$, defining the base-period share of variable cost as $\alpha = w_0 q_0 / y(x_0)$, and defining the ratio of marginal products as $R = [y(x_1)/y(x_0)]$, we can rewrite (8) as:

$$\frac{n_1}{n_0} = \frac{R - \alpha}{1 - \alpha}. \tag{9}$$

Now it is easy to compute the bias in hedonic price indexes that measure the quality superiority of the new model over the old model by the ratio R. Let us consider a value for R of 1.25, equivalent to the 25 percent annual rate of price decline that emerges from many studies of mainframe and personal computers. Then the proper comparison based on the net revenue ratio comes out at 1.25 only if the variable cost share (α) is zero. The net revenue ratio ranges from 1.28 at $\alpha = 0.1$ to 1.5 at $\alpha = 0.5$ to 3.5 at $\alpha = 0.9$. Thus if the true variable cost ratio is one-half, the hedonic method understates the increase in the quality of computers (and their rate of price decline) by half.

Clearly, Denison has identified an important problem that has been ignored previously. Yet it is not fatal. Rough order-of-magnitude calculations of the variable costs involved in operating a computer center would suffice to avoid most of the bias. And computers are special. There has not been any such radical change in labor used relative to the characteristics of most other types of capital goods. Trucks may be more fuel efficient but still require one driver, broadcast TV cameras still require one cameraman, electric drills and other power tools still require one operator, and so on.

The Criterion of Consumption Foregone

Daunted by the difficulties of implementing the correct method 3 across the board, Denison rejects it as infeasible. His final section then ponders the relative advantages of the criterion of consumption foregone as compared with the alternative of using unmodified method 1 (which, as in equation 6 above, ignores cost-reducing shifts in production technology that allow an increase in the quantity of productive characteristics relative to base-period production cost). The consumption foregone method simply deflates the nominal value of investment goods by the consumption goods deflator, while method 1 corresponds roughly to the practices used in the official investment deflator for goods other than computers. Denison, who had previously (1989) endorsed the consumption foregone criterion, now criticizes it for failing to provide any detail on changes in the relative price of investment goods, and as a result he comes back to his original (1957) preference for method 1, since this allows the development of "different price indexes . . . to deflate different capital goods."

We note that this distinction is of little practical importance. The 1929–91 annual growth rates of the official deflators were 3.45 percent for consumption, 3.64 percent for fixed non-residential investment, and 3.29 percent for producers' durable equipment (PDE). These differences are trivial compared to the three percent annual difference between the official PDE deflator and that developed for my book for 1947–83, or the 20-to-25 percent annual rate of price decline for computers.

Conclusion: Is Half a Loaf Better than None?

In correspondence and in the body of his paper, Denison recognizes that my chapters on aircraft and electric generating plants represent a full-blown implementation of method 3. He also recognizes that some of my other empirical work represents a significant step toward method 3, including the adjustments

for improved energy efficiency of automobiles and appliances, and the reduced repair frequency of TV sets. Nevertheless, he rejects method 3 because it is currently difficult to provide a *comprehensive* set of investment goods deflators based on method 3, even though it is clearly feasible for particular products with good data. Thus, while he recognizes that my PDE deflator is biased upward because of its incomplete implementation of method 3, he nevertheless recommends going back to method 1 that contains a much larger upward bias.

Through the centuries scientists have adopted new paradigms when the old ones have been rendered obsolete, even if instantaneously they could not provide precise measures of the new concepts. Only method 3 makes any sense as a theory that provides a unified approach to both economic growth and economic behavior at the individual and industry level. Only method 3 allows us to explain why for some products net revenue is not proportional to cost, or why used asset prices for assets of a given age are not proportional to cost. Only method 3 allows us to allocate properly the fruits of research and development, crediting the manufacturers who do the R&D with productivity gains rather than the users who (like airlines) do virtually no R&D. Only method 3 treats the first-generation DC-8 jet aircraft that generated ten times more net revenue than the old DC-7 as ten times the capital, not just as a larger version of the clunky fuel-guzzling piston DC-7 lumbering along at 350 miles per hour (as is implied by a method 1 treatment of aircraft).

In the end, Denison wants our measures of capital and output to ignore a "vastly greater" range of choice and quality available to today's consumer, including the ability to fly across the continent for roughly 10–15 times the average hourly wage, instead of 400 times the average wage as in the 1930s. I want to go as far as possible toward quantifying the increase in consumer welfare in a way that makes microeconomic sense. For me, the "half a loaf" that I have achieved is a way-station to "3/4 loaf" in the next generation and maybe a "full loaf" in the generation after that. Should we follow the other route and prefer no loaf at all?