Measuring the Spillovers from Technical Advance: Mainframe Computers in Financial Services

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Measuring the social gains from recent technological advances is difficult because there are no real output indexes for some important adopters. Measurement methods that infer the willingness to pay of the adopting industries from the derived demand curve for a new technology overcome this difficulty. The derived demand for high-speed computers for use in banks, finance, and insurance is shown to imply a very large social gain to computerization that was not captured by manufacturers of computers.

An important component of the social benefits of technical advances is the spillover to the customers of the advancing sectors. Process innovations lower costs and therefore prices, to the benefit of downstream sectors. New or improved products whose prices do not fully reflect their enhanced downstream value yield a similar spillover. Measurement of the quantitative importance of such spillovers[1] contributes to our understanding of the role of technical advance in long-term economic growth,[2] and is central to the formation of public policies towards innovation.[3] As Zvi Griliches (1979) points out, important postwar technological advances, such as those in electronics and health, have largely benefited downstream sectors in which the spillovers are hard to measure. The downstream sectors—services, government, health care, etc.—lack sensible measures of real output, so that calculation of the impact of the new technology on productivity or cost is difficult. The goal of this paper is to devise methods for the measurement of spillovers which do not depend on the existence of real output indexes in the downstream sector. Instead, the value spilled over will be inferred from the demand curve of the downstream sector for the output of the advancing sector.

If an innovation serves only to lower the price of a consumption good, the resulting area under the demand curve for the good (adjusted for income effects) is a welfare index: calculating it yields the value of the spillover. In the more usual case of technological progress in an intermediate goods industry, the welfare economics are more complicated. The results of this paper show that the area under the *derived demand curve* for an intermediate input (adjusted for income effects) is a welfare index as well. The derived demand curve is the relationship between the price and quantity of an input, allowing for equilibrium in the output market. Along the derived demand curve, input quantity demanded will increase in response to a fall in input price both because of substitution out of other factors and because a lower price for one input will usually

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[1]Another kind of "spillover" is also discussed in the economics of technology—the external benefits of knowledge creation. When investment in new knowledge by one firm "spills over" to other firms, a positive externality arises within the advancing sector itself. For an attempt to quantify that other kind of spillovers, see Adam Jaffe (1984).

[2]See Robert Fogel (1964) and Paul David (1975) for discussions of the economics of major innovations and for discussion of the importance of the railroads in nineteenth-century U.S. economic growth.

[3]See Edwin Mansfield et al. (1977) for a discussion of the welfare economics of spillovers. They also measure the spillovers from a number of recent technological advances.

lead to an expansion of output.[4] If price in the upstream sector falls, the area under the demand curve for its output measures the sum of the increased producer's surplus in the downstream sectors plus the consumer's surplus of final demanders.

The real quality-adjusted price of computers has fallen rapidly since they first became commercially available thirty years ago, largely because of technological advances in the high-speed computer sector itself and advances in electronic components such as integrated circuits. Further, a very large fraction of computer sales is to sectors such as services and government in which real output is poorly measured. The national income accounting convention for these sectors has been that real outputs are measured by inputs, and research has not yet provided convincing alternative indexes of real output. As a result, total factor productivity (*TFP*) indexes for these sectors measure an accounting identity rather than the output and productivity effects of the technical change in computing. Inferring the value of the technology from adopters' willingness to pay is an attractive, feasible alternative.

This paper will calculate the spillovers from advances in general purpose ("mainframe") computers to the financial services sector (banking, insurance, and brokerage) from 1958 to 1972. This sector made up a large fraction of private demand for computers. The indexes calculated will measure welfare under two central assumptions. First, existing quality-adjusted price indexes for computers are reliable. Second, the financial services sector is competitive on those margins not fixed by regulation. Competition will lead the sector to act as the agent of its customers. Thus we can treat purchases of computers by the services sector as if they were made for those customers, and infer the gain to the customers from service's derived demand for computers.

The area under the demand curve for a product can be measured either by econometric techniques or by index-number techniques. (This is the analog of the distinction between econometric production function estimation and the calculation of an index of *TFP* growth.) In this paper, index-number techniques based closely on those of Douglas Caves, Laurits Christensen, and Erwin Diewert (1982) will be used. These techniques measure the real resource cost of providing consumers with a given level of utility, or the real costs of a given level of output in producer sectors which use financial services. These costs were lowered substantially by falls in the price of computers as inputs to the financial services sector.

I. The Welfare Analysis of Derived Demand

The theoretical model used in the spillover calculation has three elements. The first is an upstream sector (computers in the application reported below) which produces a vector of outputs Z_1 at quality-adjusted prices W_1. Both Z_1 and W_1 are observable to the analyst. It is useful to think of W_1 as falling rapidly over time because of technical progress.[5]

The second element in the model is the downstream sector (banking, finance and insurance) which produces outputs Q_1 using Z. The vector Z includes all of Z_1 as elements. The prices of all inputs are denoted W and assumed to be observable to the analyst. Each output in Q_1 has an endogenous price and quality; the vectors of these are called P_1 and Δ_1. Both P_1 and Δ_1 are unobservable to the analyst. This unobservability arises because product quality in this sector is difficult to measure quantitatively. Only expenditures on each good, j, in the sector $p_j \times q_j$, are observable. The technology in this sector is represented by a con-

[4] This is Alfred Marshall's usage: the demand for the input is "derived" from that for the output (*Principles of Economics*, 1948, p. 381). The alternative usage of "derived demand" to mean "demand for an input holding the price of the output fixed" is incorrect and should be discontinued.

[5] If there is substantial market power in the Z_1 sector, prices will fall more slowly than they otherwise might, and downstream sectors will reap smaller benefits from technical advance in any given period. This paper will only quantify the benefits actually reaped by the downstream sector from the actual price fall, not the potential benefits.

stant returns to scale production function for each element of Q_1:

$$q_j = F_j(\delta_j, Z^j), \tag{1}$$

where δ_j is output quality, and Z^j the inputs used in this particular industry. Price and quality setting in the Q_1 sector are competitive, except that the government regulates prices in some industries in this sector (for good or ill). For convenience, let the regulated industries be the first R elements of Q_1. Let g_j stand for the government-set price in industry j, and let G_R and Q_R refer to the vectors of prices and quantities in the R regulated industries. The rule by which government gets G_R will be discussed below. For firms under regulation, the behavioral assumption is that they still act competitively with respect to the price, quality, or marketing variables they do control.

The third element of the model is made up by the consumers and the firms in other industries who are customers of the Q_1 sector. Both kinds of customers have demands which depend on the quality and the price of outputs from the Q_1 sector. Both kinds of customers buy non-Q_1 goods as well; the prices of these are taken to be observed.

This section has two purposes: to show that the unobservability of Q_1, P_1, and Δ_1 is of no consequence in attempting to measure the social value of the fall in W_1, and to derive index-number formulae which yield an estimate of that value. For brevity, I explicitly treat only the case in which all of the output of the Q_1 sector is purchased by consumers.[6]

A. *Derived Demand by Competitive Industries*

The cost function for industry j is denoted $C_j(q_j, \delta_j, W)$. Consumers buy not only Q_1 but also other goods Q_2 at prices P_2. These prices are taken to be observable. Consumers have utility function $u = U(Q_1, \Delta_1, Q_2)$, and associated expenditure function $E(u, P_2, P_1, \Delta_1)$. The downstream industries are competitive with supply functions:

$$p_j = g_j, \qquad j \in R \tag{2}$$

$$p_j = \frac{\partial C_j(q_j, \delta_j, W)}{\partial q_j}, \qquad \text{otherwise,}$$

$$-\frac{\partial E}{\partial \delta_j} = \frac{\partial C_j(q_j, \delta_j, W)}{\partial \delta_j} \qquad \forall j$$

Let M_R be an R vector and $X'Y$ be the inner product of vectors X and Y. Then we have the result that market equilibrium will act so as to minimize the sum of social costs plus (marginal) regulatory costs:

Result 1. *If consumers are expenditure minimizers and firms in the Q_1 sector are competitive cost minimizers, then Z, Δ_1 and Q solve*:

$$\min E = P_2'Q_2 + \sum_{j=1}^{J} W'Z^j + (G_R - M_R)'Q_R \quad **$$

$$\textit{subject to} \quad u = U(Q_1, \Delta_1, Q_2) \quad *1$$

$$\textit{subject to} \quad q_j = F_j(\delta_j, Z^j) \quad j = 1, \dots, J \quad *2$$

when M_j is evaluated at marginal cost in regulated industry j.

PROOF:

The proof, in the Appendix, shows that the first-order conditions for $**$, taken together with the definitions of cost and expenditure functions, are the same as (2).

To understand the intuition and the utility of Result 1, first consider the case in which there are no regulated industries in the Q_1 sector. Under competition, each p_j will maximize the sum of producer's and consumer's surplus (ignoring income effects for brevity) in market j. As a result, we can treat these industries as if they were owned by consumers. Calculating a welfare index on the basis of Result 1 will involve using P_2 and

[6]An earlier, longer version of this paper has a fuller treatment. See also fn. 27.

W, since P_1 does not appear. This calculation is based on the prices of inputs into the Q_1 sector instead of outputs: it is the calculation of a cost of living and of making Q index. From this viewpoint, there is no more difficulty with the lack of a consistent price index for insurance services than with a lack of a consistent price index for refrigeration services. In the latter case, I calculate the real cost-of-living index based on the inputs the household purchases in order to make refrigeration services, such as refrigerators and electricity. In the former case, we can calculate an index using the inputs bought by the insurance industry "for" households.

More formally, let $E^*(u, P_2, W)$ be the solution to ** in the case where there are no regulated industries. It is immediate from the usual envelope theorem argument that

$$z_k = \sum_j z_k^j = \frac{\partial E^*(u, P_2, W)}{\partial w_k}.$$

As a result, integration of the derived demand functions Z will yield estimates of E^*. This calculation is taken up below.

This argument cannot be applied to the regulated industry case without alteration. Result 1 is stated as if $G_R - M_R$ is exogenous, since competitive price-regulated firms act as if they cannot affect these margins. But quality competition renders the level of marginal cost endogenous, and even the government-set prices of regulated industries must surely be treated as responsive to costs in the long run. Obviously, no general results can be obtained in the regulated industry case, but two important models of regulated industry price setting have similar implications.

First, consider the model of government behavior in which prices in the long run are ρ_j percent greater than marginal costs in industry j. Let $\tilde{E}(u, P_2, W, G_R - M_R)$ be the solution to ** in general. Differentiation of $\tilde{E}$ does not determine all of the equilibrium values since $G_R - M_R$ is endogenous. The observable derived demand curves will take the form $Z^*(u, P_2, W) = \tilde{Z}(u, P_2, W, G_R(P_2, W) - M_R(P_2, W))$. The regulations imply

$$g_j - m_j = \rho_j \frac{\partial C_j(\tilde{q}_j, \tilde{\delta}_j, W)}{\partial q_j}$$

where the tildes denote equilibrium values. By how much will an increase in w_k lower social surplus?[7]

$$d\tilde{E}/dw_k = \sum_j z_k^j + \sum_j \rho_j Q_j \left[\frac{\partial^2 C_j}{\partial q_j^2} \frac{\partial \tilde{q}_j}{\partial z_k} + \frac{\partial^2 C_j}{\partial q_j \partial \delta_j} \frac{\partial \tilde{\delta}_j}{\partial z_k} \right].$$

If the equilibrium effect of higher factor prices is to raise marginal costs, the term in square brackets will be positive. As a result, integration of the demand curves Z^* will understate the welfare effects of changes in W.

This result appears to be in conflict with the observation that regulated-industry quality competition can lead to too rapid adoption of technologies whose prices are falling over time (Nathan Rosenberg and David Mowery, 1982). The conflict is only apparent. Quality competition may in fact lead to too much demand for some inputs Z, relative to the unregulated first-best. However, we are seeking an index of surplus actually achieved in the market, not of surplus that could be achieved if the regulations were removed.

The second model of regulation to consider is that of successful cartelization of the industry through regulation. Then the industry equilibrium, including the equation

[7] It is not quite right to treat $\tilde{E}$ as social costs at the margin, since the excess of price over marginal costs in the regulated industry is presumably a return to someone and therefore part of social surplus. Thus the calculation made here tends to understate social surplus. If quality competition destroys most or all of the regulatory rents, this distinction will be unimportant. (This need not always follow from quality competition: see George Stigler, 1968, and Lawrence White, 1972.)

for the regulatory price, acts to maximize profit, not social surplus. The derived demands Z will once again provide an index of what is being maximized in the market: profit, not total surplus. However, the surplus actually obtained in the market is larger than profit, since consumers do obtain some surplus. Therefore welfare indexes based on derived demand by a monopolized industry will tend to understate the true social value of upstream price changes.[8]

When certain prices are not easily observable, an opportunity to substitute theory for data arises; it is possible to use assumptions about the process by which those prices are set to replace information about the prices themselves. When the prices are set in a competitive market, it is appropriate to do exactly what one would expect: infer value from the area under the derived demand curve. When the market is not competitive, this argument fails. However, the same calculation does yield underestimates of the social gain from a decline in upstream prices.

B. *Implied Welfare Measures*

The result of the last subsection can be exploited in deriving welfare measures. Suppose we have two different time periods, 0 and 1, and wish to know how much the fall in W_1 from W_1^0 to W_1^1 benefited consumers.[9] The first task is to figure out by how much more consumers are better off in period 1 than in period 0. Answers to this question take the form of cost-of-living indexes: how much more expensive would it have been to provide period 1 utility in period 0, and how much cheaper would it have been to provide period 0 utility in period 1? The primary difference of the current model from the usual analysis of a cost-of-living index is that here I analyze the cost of living and of making Q_1, since the model (implicitly) treats the Q_1 sector as if it were owned by consumers. The relative cost of providing period 1 utility at period 0 prices is

$$C^{*1}=\frac{E^*(u^1,P_2^0,W^0)}{E^*(u^1,P_2^1,W^1)}.$$

The inverse of the relative cost of providing period 0 utility at period 1 prices is

$$C^{*0}=\frac{E^*(u^0,P_2^0,W^0)}{E^*(u^0,P_2^1,W^1)}.$$

The large body of useful results from the theory of index numbers for the standard consumer problem apply here without alteration. The derived demand curves from the market equilibrium, $Z(u,P_2,W)$, are the same ones that would come from directly maximizing the problem $**$. As a result, the marginal social value of elements of Z is revealed in the derived demand in exactly the same sense that a single consumer's demands reveal the marginal value of goods to that consumer. Any functional form assumptions about $E(\ )$ lead to function forms for the cost-of-living index which can be calculated without econometric estimation. In the regulated case, these indexes will be biased against assigning welfare gains to falls in regulated industry factor prices. I follow Caves et al. in the choice of functional form, and assume that E^* has the translog functional form in both periods 0 and 1, and further that any changes in technology or tastes between the two periods shift only the first-order terms of the translog function.[10] The practical impact of these assumptions will be discussed below.

Under these assumptions, an estimate of the real cost of living and of making Q_1 index can be calculated on the basis of the observables alone. Let E^t denote the value of E^* at time t. Let s_Z^t be the vector of shares of expenditures on Z in E^t. Similarly, s_Q^t is the vector of shares of the Q_2 consumer goods in E^t with typical elements $s_{Q,k}$. The elements of the vector (s_Z^t, s_Q^t) sum to one.

[8] This single-industry argument has been made more generally in Robert Willig's (1983) analysis of taxation in many industries with market power.

[9] In what follows, superscripts denote time periods.

[10] See Caves et al. for translog formulae.

Then (following Caves et al.),

$$(3)\quad \frac{1}{2}\log(C^{*0}\times C^{*1}) = \frac{1}{2}\left(\sum_{k=1}^{K}\left(s^0_{Q,k}+s^1_{Q,k}\right)\log\left(\frac{p^0_{2,k}}{p^1_{2,k}}\right) + \sum_{n=1}^{N}\left(s^0_{Z,n}+s^1_{Z,n}\right)\log\left(\frac{w^0_n}{w^1_n}\right)\right).$$

Suppose a cost-of-living index were calculated using incorrect price and quantity indexes $\hat{P}_1$ and $\hat{Q}_1$. (These might be the indexes available from the national accounts.) In the translog case, the percentage bias to such an index is[11]

$$(4)\quad \frac{1}{2}\left(\sum_{j=1}^{J}\left(\sigma^0_{\hat{Q}_j}+\sigma^1_{\hat{Q}_j}\right)\log\left(\frac{\hat{P}^0_j}{\hat{P}^1_j}\right) - \sum_{n=1}^{N}\left(s^0_{Z,n}+s^1_{Z,n}\right)\log\left(\frac{w^0_n}{w^1_n}\right)\right)$$

where $\sigma_{\hat{Q}_1}$ is the vector of Q_1 shares in consumer expenditure as normally defined. Calculation of this bias would reveal by how much growth in real consumption was understated because of the use of the incorrect price indexes for the Q_1 sector.

The second welfare analysis to undertake is the answer to a counterfactual question: by how much are the downstream sectors and their customers better off than if there had not been the extraordinary technical advance in the Z_1 sector? This requires some assessment of how high W_1 would have been in period 1 without the technical advance. This is clearly arbitrary in any application, but a useful baseline is to take the relative price of Z_1 in period 0 and hold it constant in the counterfactual period. Labeling the counterfactual period period 2, we have $P_2^2 = P_2^1$, $W_2^2 = W_2^1$, and $W_1^2 = I(P_2^1, W_2^1)/I(P_2^0, W_2^0)\times W_1^0$ where $I()$ is some price index formula (the translog in the application below).

If the demand for the output of an advancing sector has been estimated econometrically, measuring the gain to downstream sectors from a fall in the price-performance ratio is straightforward. One simply integrates the demand system to obtain the function E^* and directly calculates the cost of living index at the counterfactual prices W_1^2 (following Jerry Hausman, 1981). In performing this analysis, the econometrician runs the risk of out-of-sample extrapolation, since the counterfactual prices have never been observed. But if the econometric maintained hypothesis is still valid even at the counterfactual point, the resulting welfare estimates will be meaningful.

The index-number method used here requires a further assumption about what would have happened in the counterfactual no-technical-advance case. The percentage amount of spillovers is a cost of living and of making Q_1 index from the counterfactual period to period 1. As in equation (3), this will take the form:

$$(5)\quad \frac{1}{2}\left(\sum_{k=1}^{K}\left(s^2_{Q_{2,k}}+s^1_{Q_{2,k}}\right)\log\left(\frac{p^2_{2,k}}{p^1_{2,k}}\right) + \sum_{n=1}^{N}\left(s^2_{Z,n}+s^1_{Z,n}\right)\log\left(\frac{w^2_n}{w^1_n}\right)\right).$$

Since $W_1^1 = W_1^2$ and $P_2^1 = P_2^2$, (5) immediately reduces to

$$(6)\quad \frac{1}{2}\sum_{n=1}^{N1}\left(s^2_{Z,n}+s^1_{Z,n}\right)\log\left(\frac{w^2_n}{w^1_n}\right),$$

where $N1$ is the number of elements of Z_1. Note that (6) depends on the shares of Z_1 in the counterfactual period. Some method of estimating these shares must be undertaken in order to calculate the indexes. There is no best means by which to do this, so in the application I will report a sensitivity analysis with respect to s_Z^2.

The methods used here for calculating welfare gains to downstream sectors from

[11] This calculation assumes that the value of inputs equals the value of outputs in the Q_1 sector, as in national income accounting data.

upstream technical advance are familiar from single-person decision theory. Their extension here to market equilibrium, and to the case of endogenous product quality, has served primarily to clarify the accounting conventions. The greatest benefit of an explicit theory will be seen in the next section, where the appropriateness of the assumptions for the application can be rigorously assessed.

II. Mainframe Computers in the Financial Services Sector, 1958–72

In this section, Z_1 is general-purpose (mainframe) computers. The downstream sector into which computers spill over, Q_1, is the financial services sector (FSS), defined as banking, brokerage, insurance, and related businesses.[12] This is a natural application, since the FSS was an early adapter of computer technology, primarily for narrowly defined data processing activities such as bookkeeping and recordkeeping.[13] Firms in this sector variously purchased, rented, and leased mainframe computers, and purchased computer services from "service bureaus."[14] Many of the real output and price indexes used in the national accounts for industries in the FSS use an "inputs = outputs" approach.[15] I will make no attempt to construct better indexes.[16] Instead, the problem will be avoided by using the theory to treat the FSS as if it were owned by its customers.

The trick of treating a sector as the agent of its customers will be used twice. Because of the importance of service bureaus in providing computer services to the FSS, we will treat the service bureaus as if they were owned by the FSS. The fraction of the computers, other capital, labor, and intermediate inputs of the service bureaus that correspond to FSS purchases will be accounted as if they were bought by the FSS directly.[17] I will compare years for which an input-output (*IO*) table exists. The base year of 1958 had the first *IO* table following the commercial introduction of mainframe computers. Thus, period 0 is 1958.

Period 1 is set to 1972 for several reasons. Historically, few of the industries in the FSS had free-market price setting. Interest rates for the liabilities of financial intermediaries were set by various federal government bodies. Insurance prices were in part set by state regulatory bodies. Until 1975, brokerage fees on the New York Stock Exchange, were set by the SEC. The fact of regulation itself does not make our calculations irrelevant, as was shown above. A serious problem would arise in the use of the index-number methodology, however, in comparing a regulated with an unregulated period. For this reason, my calculations end in 1972 rather than with a later *IO* table, as the regulatory environment of the FSS was substantially liberalized over the 1970's. A second reason for stopping in 1972 is that extension of a quality-adjusted price index for computers past 1972 would be quite difficult. Over the 1970's, more and

[12] Financial services as defined here are sector 70 in the input/output tables of the Department of Commerce Bureau of Economic Analysis (BEA) and are SIC 60–64 and 67.

[13] See Montgomery Phister (1979, ch. 3, especially part 3.1). See Horst Brand and John Duke (1982) for an interesting review of labor-saving computer installations in banking.

[14] As late as 1975, 71 percent of the banks using computer services purchased them from an external service bureau. Many small banks purchase computer services from larger money-center banks with which they are in correspondent banking services relationships. Insurance companies and brokers tend to own or lease computers, not buy computer services. See Philip Wyborg et al. (1977, p. 22).

[15] See John Kendrick (1982b) for summary and useful discussion of BEA methods of estimating real output in the services sector generally. Within the FSS, the BEA estimates real output for banking, credit agencies other than banks, and security and commodity brokers and services by a weighted labor-hours indicator. Insurance brokers, agents and services have real outputs estimated by an index of transactions volume.

[16] Extension of the transactions volume approach to commercial banking has been proposed by John Gorman (1969). Jerome Mark (1982) and Brand and Duke report some estimates using this approach.

[17] Service bureaus come into existence for a variety of reasons. In this instance, the most important motivation is probably to spread lumpy computer capital over many users. Thus it is probably appropriate to draw no distinctions between input prices at service bureaus and in the FSS.

TABLE 1—EXPENDITURES AND SHARES OF BEA SECTOR 70

	Expenditures, Current 10^6 (1)	Share in Direct Cost (2)	Share in Total Cost (3)	Share in Cost with BEA 73 Added (4)
1958				
Labor	8492	.405	.545	.574
GP Computers	34	.00159	.002150	.00225
Other Capital	793	.038	.051	.053
FSS (BEA 70)	5389	.257	–	–
Business Services (BEA 73)	1025	.049	.066	–
Other Interm.	5231	.250	.336	.370
1972				
Labor	28595	.422	.548	.597
GP Computers	1237	.0183	.0237	.0254
Other Capital	3959	.0584	.0759	.1050
FSS (BEA 70)	15562	.2298	–	–
Business Services (BEA 73)	6033	.0891	.1156	–
Other Interm.	12321	.1819	.2362	.2724

more of the tasks previously assigned to mainframe hardware were moved to software as a result of operating systems advances. At the same time, competition between small mainframes and larger minicomputers began to increase.[18]

A. *Share and Price Calculations for the FSS*

The first task is to construct factor shares and factor prices for the FSS in 1958 and 1972. The approach used here relies heavily on data developed by Frank Gollop and Dale Jorgenson (1980, 1983) Jack Faucett Associates (JFA) (1979, 1977), and Barbara Fraumeni and Jorgenson (1980). Table 1 shows expenditures and shares of the FSS in 1958 and 1972, first giving the gross (current) dollar expenditure on six factors of production. These differ from JFA in that the consumption by the FSS of its own output as an intermediate input, and the consumption of the output of business services by the FSS are treated separately.[19] The remaining columns show the cost shares of the remaining four factors of production after these two inputs are treated as if they were made in the FSS. The correction for purchases of own-input takes the form (using superscripts to indicate columns) $s_j^{(3)} = s_j^{(2)}/(1 - s_{70}^{(2)})$ for all inputs j other than the FSS (BEA 70) input. In column 4, inputs into the business services sector are distributed to the FSS. Since the output of the business services sector is treated as if it were produced in the FSS, it is necessary to allocate labor, intermediate inputs, and computer and other capital purchased by the business services industry to the FSS. Thus $s_j^{(4)} = s_j^{(3)} + s_{73}^{(3)} \times s_j^{73}$, where s_j^{73} is the share of input j into the business services sector.[20]

The capital input has been divided into two components, computer and noncomputer. Here "computer" means only the CPU and memory of a mainframe computer system. Expenditures on computers are calcu-

[18]Robert Gordon (1985) reports, however, a slowing in the rate of decline in quality-adjusted computer prices after 1972. I therefore speculate that extension of my results to the present would find slowing returns to computerization.

[19]These are calculated from the 1958 and 1972 *IO* tables, as reported in the *Survey of Current Business*, November 1964, February 1979, and April 1979. Service Bureaus are a subset of BEA 73, "Business Services."

[20]This procedure underestimates the share of computer services in the FSS. The factor shares used in this calculation are for the entire services sector. Firms in the FSS, however, tend to concentrate their business services purchases in the computer service firms more than the average firm in the economy.

lated as if the computers were rented, regardless of their actual ownership. Rental prices are list prices for different model computers as reported by Montgomery Phister (1979). The inventory of privately held computers by model and of computers held in banking and insurance in Phister is used to weight the rentals.[21]

The treatment of complements to computers such as software and computer peripherals (especially mass storage devices) deserves some comment. There was considerable technical progress in software and peripherals over the period studied, both caused by and enhancing computerization. In such circumstances, there is no unambiguous definition of "the benefits of cheaper computers," if this term is something that is added together with "the benefits of improved software and peripherals." Some of the increase in the quantity of computers demanded actually caused by technical advance in those other inputs may well be attributed to technical advance in computers in my calculations. On the other hand, falls in the price of computers led to increased demands for the complements, which is not counted as increases in value here.[22] My calculations underestimate the total value of computers plus peripherals in the FSS. One might further adopt the convention that the correct definition of the area under the demand curve for right shoes per se is one-half the area under the demand curve for shoes. On this convention, it is not clear whether I over- or underestimate the area under the demand curve for computers per se.

The small share of computers in 1958 FSS expenditures, just over two-tenths of a percent in column 4 in Table 1, naturally raises a question about the validity of the translog approximation to E^* over such a broad range. It would be very troubling if the behavior of the isoquants near the computers = 0 axis was driving the calculations. Consideration of (4) and (6) shows this concern to be unfounded. If the share of computers in 1958 were doubled or halved, the calculations would change little. This intuition is straightforward: roughly speaking, (6) calculates the size of a welfare triangle. The translog works better if not literally extended to the axes, but evaluated at some "small" value at which the demand curve "almost" cuts the axis. What determines the size of the triangle is not how small small is, but rather how high the price is at which the demand curve almost cuts the axis.

TABLE 2—PRICE INDEXES

	1972 = 1.00
Labor	.482
GP Computers	
Gordon	333.62
Chow	19.37
Other Capital	.704
Intermediate	.6607
FSS (BEA 70)	.5354

Price indexes for the FSS and for the inputs into it are reported in Table 2. The index for the FSS itself is the implicit deflator as calculated by the BLS.[23] The wage rate is taken directly from Gollop and Jorgenson (1983). The price index for remaining intermediate goods is calculated using the JFA (1977) procedure. The noncomputer capital service price is calculated using the JFA data following the procedure of Fraumeni and Jorgenson, except that real estate sector capital is excluded.

It is clear from the formulae in (4) and (6), and from the geometrical argument made above, that the welfare inferences drawn here will be quite sensitive to the quality-adjusted price index for computers. A large literature on the economic measurement of quality-adjusted prices for computers has followed on the work of Gregory Chow (1967).[24] This

[21] See Phister's Tables II.2.10, II.3.11.4, II.3.11.5. Expenditures on noncomputer capital are calculated by first following the JFA procedure and then subtracting out the computer expenditures.

[22] Both of these statements are contingent on the empirical assertion that falls in software and peripherals prices are inadequately captured in the national accounts. In fact, both are treated the same way as computers, with no quality correction to their price indexes.

[23] "Time Series Data for Input-Output Industries," BLS Publication 2018 (1979).

[24] See Ernst Berndt (1982) for conditions under which the existence of a well-defined price-performance index is guaranteed.

literature has recently been both summarized and substantially advanced by Robert Gordon (1985). I use two different price indexes in the calculations, the one from Gordon's preferred specification of computer quality and my extension of Chow's index forward to 1972. Both indexes use hedonic methods. I use my extension of Chow's price index because among the available indexes covering the period 1958–72, it shows the smallest fall, 19.08 percent per year in nominal terms. Gordon's index shows a rate decrease of 33.97 percent per year for that period. Given Gordon's observation that most of the important differences between the two price indexes occur before 1960, the two indexes reflect a realistic upper and lower bound on the price at which the demand curve for computers cuts the axis. Both indexes cover only the basic CPU and memory, not any peripherals, so they are consistent with my definition of the computer input.

A final reservation one might have about this application is that a great many things have been changing in the economic environment of the FSS other than the fall in the price of computing power. One class of changes in the economic environment can be captured by changes in income, or in the prices of other inputs or of other consumer goods. The flexible functional forms used here for preferences and for technology do not put restrictions on the elasticities of substitution between computers and other inputs in financial services, or on the income or price elasticity of demand for the output of the financial services sector. Price and income changes are well treated in index-number methods. If increased computerization is to be attributed to rising real wages in the financial services sector, or if the increase in the size of the sector is to be attributed to income-elastic demand for its output, such factors have been accounted for in the calculations.

Another class of changes in the economic environment is not "priced out." This includes demographic shifts which change demand, independent technical progress in the FSS, and so forth. Slightly stronger assumptions are needed here. The results of Caves et al. continue to hold if there are shifts in the first-order coefficients of the translog E^* between the two periods, but not shifts in the second-order coefficients. As a practical matter, this means that the model allows arbitrary shifts between the two periods in the desirability of any input or of any good, as long as these shifts do not change the demand elasticities. Thus independent technical progress in the FSS can be labor saving and computer using, but cannot change the elasticity of substitution between labor and computers. These are defensible assumptions, but, if they are false, then econometric methods could go beyond the index-number methods employed here to get a better answer.

B. *Biases to Cost Indexes*

This subsection reports calculations of the biases to the cost-of-living index and to a cost of (nonfinancial) production index from using the FSS price index from the national accounts. The downstream sector considered here is the private nonfinancial domestic economy. In the input-output system, it consists of the personal consumption expenditures component of final demand (*PCE*) and intermediate-input demand by all private business outside the FSS, which we call the private nonfinancial business economy (*PNFBE*).[25] These two sectors together we call the private domestic economy (*PDE*). The shares of the FSS in these sectors are shown in Table 3.[26]

Table 4 shows the results of calculating (4), the percentage bias to the conventional cost-of-living index caused by using the FSS implicit deflator as the price index for the sector.[27] The size of the bias is sensitive to

[25]In the 1972 *IO* table, the *PNFBE* is defined to include BEA sectors 1–69 and 71–76. In the 1958 table, it is 1–69, 71–76, and 81–83.

[26]It may be somewhat surprising that the share of the FSS in *PCE* is so much larger than in *PNFBE*. What is behind this is that the sales of the FSS to *PCE* are approximately equal to its entire sales as an intermediate input. Almost half of the intermediate-input sales of the FSS are to itself, so that after they are netted out the contribution to the *PNFBE* is considerably smaller.

[27]No important difference arises in calculating the real input cost index for the *PNFBE*. (See Caves et al.) However, some additional assumptions are needed to

TABLE 3—FSS SHARE IN DOWNSTREAM SECTORS' EXPENDITURES

	Downstream	
	1958	1972
PCE	.0407	.0529
PNFBE	.0253	.0213
Total *PDE*	.0320	.0358

TABLE 4—BIASES TO .5 ($C^{*0} \times C^{*1}$)

Bias	*PCE*	*PNFBE*	*Entire PDE*
Gordon	.00587	.00257	.00408
Chow	.00384	.00172	.00269

the computer price index used. The economic importance of the estimated bias can be illuminated by an evaluation of the "outputs = inputs" approach to real price and output indexes. From 1958 to 1972, the implicit deflator for the FSS grew at 4.56 percent a year, on average. An alternative price index can be calculated by solving (4) for that $\hat{P}$ which gives a bias of zero. Economically, this is the price index implied by a perfectly competitive FSS with no internal technical progress. The annual rise in this price index was 3.98 percent (Chow index) or 3.67 percent (Gordon index). Thus either computer price index implies substantially faster real growth in the FSS than does the implicit deflator, even under the conservative assumption of no internal technical progress.

These figures are not out of line with other indexes of real output based on the "transactions" approach. Horst Brand and John Duke calculate a transactions-based real output index for commercial banks for the period beginning in 1967. Through 1972 it advances 1.5 percent per year faster than the deflator. Similarly, the transactions index of real output for the insurance sector used in the national accounts advances about 1.5 percent faster than the older, "liquidity" index.

C. *Spillover Calculations*

The size of the downstream welfare gains resulting from the fall in the price-performance ratio of computers can be estimated using (6). Results for this calculation are shown in Table 5 for each of the two price indexes and for three counterfactual shares of computers, s_Z^2. Given that the counterfactual is a 1972 world but with the 1958 relative price of computers, the base case (reported in the left column of the table) is $s_Z^2 = s_Z^1 = .91E^{-4}$. Many economic assumptions could have led to this share actually arising in 1972. For interpretational purposes, I prefer to use the assumptions of an expenditure elasticity of demand for computers of unity, and that computers are separable from everything else in E^*.[28] Then to get comparison cases, I maintain the separability assumption and assume that the expenditure elasticity of demand for computers is larger, taking on the values 2 and 3 in the second and third column of the table.[29]

The interpretation of these figures is as the amount by which consumers would be worse

TABLE 5—SPILLOVER CALCULATION: *PCE*

Case	(1)	(2)	(3)
s_Z^2	.000091	.000164	.000296
Spillover (Gordon) ($\$10^6$)	417	750	1351
Spillover (Chow) ($\$10^6$)	225	405	729
Expenditures ($\$10^6$)	68	68	68

calculate cost of living and of making Q_1 indexes for the two different customers of the FSS, final demand and intermediate demand. This calculation implicitly assigns the producer's surplus gained in the FSS, if any, to the two groups of customers in proportion to their sales. Further, the assertion that the presence of regulation leads to an underestimate of the size of the gains to each group of customers is obviously stronger than the result obtained in Section I. In particular, systematic cross subsidy between business and consumer customers of the FSS would invalidate that result.

[28] This would be true if the real income elasticity of demand for financial services is unity, the output elasticity of demand for computers in the FSS is also unity, computers are separable from other inputs in FSS production, and FSS outputs are separable from other goods in demand. These obviously unrealistic assumptions are used merely to provide an economic motivation for the nonbase cases.

[29] Income elasticities of demand for the FSS substantially greater than unity are reported by Kendrick (1982a).

off in 1972 if the real (rental) price-performance ratio for computers used in the FSS had not fallen from its 1958 level. For example, if we take the base case s_Z^2, consumers in 1972 would have been willing to pay $225 million (Chow index) or $417 million (Gordon) for this price decrease. Correspondingly higher estimates of this willingness to pay would be obtained if, for any reason, the share of computers in expenditures would have risen above its 1958 level even without the fall in computer prices. To put these figures in perspective, the amount spent by the FSS "for" consumers in renting computers in 1972 was $68 million. Thus if we were to draw the derived demand curve for computers used in the FSS and put in the 1972 price, the consumer's surplus triangle would be five or more times the size of the $P \times Q$ box.

Similar figures would be obtained for the cost indexes of business customers of the FSS: the analog to Table 5 for them is essentially proportional to it.

I draw the following conclusion from these calculations: compared to expenditures on computers, the spillover to adopters of computers and their customers has been large. The present analysis has used a sector in which computers are particularly valuable, so that the finding might not generalize to the rest of the economy.[30] On the other hand, the price-performance ratio for computers has (conservatively) fallen another order of magnitude for computers since 1972. So in current (1986) terms, the downstream benefits of technical progress in mainframe computers since 1958 are conservatively estimated at 1.5 to 2 orders of magnitude larger than expenditures, at least in this high-value use.

Appendix: Proof of Result 1

Let λ be the Langrangian corresponding to $*1$, and let μ be the vector of Lagrangians for $*2$. Then the first-order conditions for the problem $**$ are

$$\text{(A1)} \quad Q_1\colon\ \lambda \frac{\partial U(Q_1, \Delta_1, Q_2)}{\partial q_j} = G_j - m_j + \mu_j \qquad j = 1, \dots, R$$

$$Q_1\colon\ \lambda \frac{\partial U(Q_1, \Delta_1, \tilde{Q})}{\partial q_j} = \mu_j \qquad j = R+1, \dots, J$$

$$\text{(A2)} \quad Q_2\colon\ \lambda \frac{\partial U(Q_1, \Delta_1, Q_2)}{\partial q_k} = p_{2,k} \qquad \forall k$$

$$\text{(A3)} \quad Z\colon\ w_j = \mu_j \frac{\partial F_j(\delta_j, Z^j)}{\partial Z_n^j} \qquad \forall j$$

$$\text{(A4)} \quad \Delta_1\colon\ \lambda \frac{\partial U(Q_1, \Delta_1, Q_2)}{\partial \delta_j} = -\mu_j \frac{\partial F_j(\delta_j, Z^j)}{\partial \delta_j} \qquad \forall j$$

plus the constraints ($*1$) and ($*2$). Compare this system to the definitions of expenditure and cost functions:

$$\min P_1'Q_1 + P_2'Q_2 + \hat{\lambda}(u - U(Q_1, \Delta_1, Q_2))$$

$$\text{(A5)} \quad Q_1\colon\ \hat{\lambda} \frac{\partial U(Q_1, \Delta_1, Q_2)}{\partial q_j} = p_j \qquad \forall j$$

$$\text{(A6)} \quad Q_2\colon\ \hat{\lambda} \frac{\partial U(Q_1, \Delta_1, Q_2)}{\partial q_k} = p_{2,k} \qquad \forall k$$

$$\min W'Z^j + -\hat{\mu}_j\big(q_j - F_j(\delta_j, Z^j)\big)$$

$$\text{(A7)} \quad Z\colon\ w_j = \hat{\mu}_j \frac{\partial F_j(\delta_j, Z^j)}{\partial Z_n^j} \qquad \forall n$$

plus the constraints. From the envelope the-

[30] But see Manuel Tratjenberg's (1985) estimates of the external benefits of CAT scanners: Tratjenberg also provides an interesting discussion of the (difficult) welfare economics of technology adoption in the health sector.

orem we know that $\hat{\mu}_j$ is marginal cost and that

$$\frac{\partial E(u,P_2,P_1,\Delta_1)}{\partial \delta_j} = -\hat{\lambda}\frac{\partial U(Q_1,\Delta_1,Q_2)}{\partial \delta_j}$$

$$\frac{\partial C_j(q_j,\delta_j,W)}{\partial \delta_j} = \hat{\mu}_j\frac{\partial F_j(\delta_j,Z^j)}{\partial \delta_j},$$

so that (2) implies

$$\text{(A8)} \quad \hat{\lambda}\frac{\partial U(Q_1,\Delta_1,Q_2)}{\partial \delta_j} = -\hat{\mu}_j\frac{\partial F_j(\delta_j,Z^j)}{\partial \delta_j} \qquad \forall j.$$

At $mc_j=\mu_j$, for $j=1,\dots,R$, the sets of equations (A1)–(A4) and (A5)–(A8) are identical.

REFERENCES

Berndt, Ernst, "Quality Adjustment in Empirical Demand Analysis," mimeo., Sloan School of Management, MIT, 1982.

Brand, Horst and Duke, John, "Productivity in Commercial Banking: Computers Spur the Advance," *Monthly Labor Review*, December 1982, *105*, 19–27.

Caves, Douglas W., Christensen, Laurits R. and Diewert, W. Erwin, "The Economic Theory of Index Numbers and the Measurement of Input, Output and Productivity," *Econometrica*, November 1982, *50*, 1393–414.

Chow, Gregory C., "Technological Change and the Demand for Computers," *American Economic Review*, December 1967, *57*, 1117–30.

David, Paul A., *Technical Choice, Innovation, and Economic Growth*, London: Cambridge University Press, 1975.

Faucett, Jack (and Associates), *Regional Input-Output Tables for the United States*, Report to the U.S. Bureau of Labor Statistics, Washington, 1977.

______, *Development of Capital Stock Series By Industry*, Report to the U.S. Bureau of Labor Statistics, Washington, 1979.

Fogel, Robert W., *Railroads and American Economic Growth: Essays in Econometric History*, Baltimore: Johns Hopkins Press, 1964.

Fraumeni, Barbara and Jorgenson, Dale, "The Role of Capital in U.S. Economic Growth, 1948–1976," in G. von Furstenberg, ed., *Capital, Efficiency, and Growth*, Cambridge: Ballinger, 1980, ch. 3.

Gollop, Frank and Jorgenson, Dale, "U.S. Productivity Growth by Industry, 1947–1973," in J. Kendrick and B. Vaccara, eds., *New Development in Productivity Measurement and Analysis*, Chicago: University of Chicago Press, 1980, ch. 3.

______ **and** ______, "Sector Measures of Labor Cost for the United States, 1948–1978," Discussion Paper No. 963, Harvard Institute for Economic Research, 1983.

Gordon, Robert J., "The Postwar Evolution of Computer Prices," mimeo., Northwestern University, November 5, 1985.

Gorman, John A., "Alternative Measures of the Real Output and Productivity of Commercial Banks," in Victor Fuchs, ed., *Production and Productivity in the Service Industries*, NBER *Studies in Income and Wealth*, No. 34, New York: Columbia University Press, 1969, ch. 9.

Griliches, Zvi, "Issues in Assessing the Contribution of R&D to Productivity Growth," *Bell Journal of Economics*, Spring 1979, *10*, 92–116.

Jaffe, Adam, "The Effects of Market Demand, Technological Opportunity, and Research Spillovers on R&D Intensity and Productivity Growth," mimeo., Harvard University, 1984.

Hausman, Jerry A., "Exact Consumer's Surplus and Deadweight Loss," *American Economic Review*, September 1981, *71*, 662–76.

Kendrick, John, (1982a) *Interindustry Differences in Productivity Growth*, Washington: American Enterprise Institute, 1982.

______, (1982b) "Measurement of Output and Productivity in the Service Sector," presented at the ARA/Wharton Conference on the Future of the Service Economy, November 1982.

Mansfield, Edwin et al., *The Production and Application of New Industrial Technology*, New York: W. W. Norton, 1977.

Mark, Jerome A., "Measuring Productivity in Service Industries," *Monthly Labor Review*, June 1982, *105*, 3–8.

Marshall, Alfred, *Principles of Economics*, 8th ed., New York: MacMillan, 1948.

Phister, Montgomery, *Data Processing Technology and Economics*, Santa Monica: DEC Press, 1979.

Rosenberg, Nathan and Mowery, David, "Technical Change in the Commercial Aircraft Industry," in Nathan Rosenberg, ed., *Inside the Black Box: Technology and Economics*, Cambridge: Cambridge University Press, 1982, ch. 8.

Stigler, George, "Price and Non-Price Competition," *Journal of Political Economy*, January-February 1968, *76*, 149–54.

Tratjenberg, Manuel, "The Welfare Analysis of Product Innovations with Applications to CT Scanners," NBER Working Paper No. 1724, October 1985.

White, Lawrence, "Quality Variation when Prices are Regulated," *Bell Journal of Economics*, Autumn 1972, *3*, 425–36.

Willig, Robert D., "Sector Differentiated Capital Taxation with Imperfect Competition and Inter-Industry Flows," *Journal of Public Economics*, July 1983, *21*, 295–316.

Wyborg, Phillip S., McCarter, Pender M. and Erickson, William, *Information Processing in the U.S.: A Quantitative Summary*, Montvale: American Federation of Information Processing Societies, 1977.

U.S. Bureau of Labor Statistics, *Capital Stocks for Input-Output Industries*, Publication 2034, Washington, 1979.

______, *Time Series Data for Input-Output Industries*, Publication 2018, Washington, 1979.