Chapter 4

HIGH-TECH INDUSTRY PRODUCTIVITY AND HEDONIC PRICE INDICES

by

Jack E. Triplett
Bureau of Economic Analysis, US Department of Commerce

Introduction

Andrew Wyckoff (1995), in a provocative paper, showed that measured growth of manufacturing output across OECD countries is very sensitive to cross-country differences in the measurement of computer prices and output. Specifically, countries that use hedonic price indices for computer equipment record higher output growth rates for their high-tech sectors. Differences in methodologies for measuring computer prices also create major inconsistencies in international comparisons of productivity.

The issues Wyckoff raises are not confined to computer prices alone. Other high-tech sectors may also be mis-measured.

Moreover, industry and sector productivity measures are vital for *understanding* productivity, because the disaggregate level is where technical change takes place, and because it is at the disaggregate level – and not for some aggregate production function – that the productivity paradigm has meaning. Once attention is turned to industry and sector productivity measures, it is not just industry outputs but industry inputs as well that need attention. The computer equipment industries are not only producers of high-tech products, they are also users of high-tech products, specifically semiconductors. Mis-measured inputs to computer production will cause mis-measurement of productivity in the computer sector, even if the output of computers is measured correctly.

This chapter first sets forth an inter-industry production model for high-tech industries. The model provides a framework for discussing hedonic price indices, hedonic output measures, and inter-industry productivity measures where hedonic measures are outputs of one industry and inputs to another. Second, it presents some preliminary estimates of the distribution of productivity increases across three inter-related high-tech sectors: high-tech semiconductor manufacturing equipment, whose contribution is the miniaturisation of electrical circuits on semiconductors, the semiconductors themselves, which account for a significant technical input into computers, and finally, computer equipment, the end-stage manufacturing level that benefits from the technological changes in the upstream industries.

The model

Production relations for high-tech industries

I begin by considering production processes for three inter-related "high-tech" sectors, computers (C), semiconductors (S), and semiconductor manufacturing equipment (E).

$$C = C\ (K, L, M, S) \quad [1a]$$

$$S = S\ (C, E, L, M) \quad [1b]$$

$$E = E\ (K, L, M) \quad [1c]$$

In equation [1a], the output of computers (C) is a function of the usual capital (K), labour (L), and materials (M) inputs, and also inputs of semiconductors (S). In turn, the output of the semiconductor industry (equation [1b]) is a function of the usual labour and materials inputs, and also two kinds of capital – computers (used in semiconductor design and for other purposes) and semiconductor manufacturing equipment (E). Finally, semiconductor manufacturing equipment (equation [1c]) is a function of capital, labour and materials inputs. A major type of semiconductor manufacturing equipment that I will discuss are steppers (aligners), the machines that reduce and create on the silicon wafer the miniaturised circuits that exist on the surface of a semiconductor.

In these three production functions, I assume no specialised labour, and also that the mix or specialisation of capital and materials is not important, except for the cases noted (semiconductor industry capital, E and C, and computer intermediate inputs, S). Non-specialisation of K, L, and M inputs to these three high-tech industries is a very special assumption that will be important for the empirical work, and is justified at a later point.

It will not do, of course, to represent the output of these high-tech industries solely in terms of simple counts of the numbers of computers, semiconductors, or steppers. Somehow, "quality" has to be brought into the analysis and needs to be modelled in a way that has empirical implications and can be represented conceptually in the production model that underlies the measurement of productivity.

At the present time, only one approach to "quality" both has empirical implications and can be given a conceptual or theoretical rationale in production theory. That approach is the one based on the *hedonic hypothesis*: Heterogeneous goods are aggregations of *characteristics*. Characteristics are variables, such as computer speed, memory size and so forth, that are both outputs for producers and productive inputs for the buyers of heterogeneous goods.

Consider first computers. Equation [2] is a modification of the production function for computers in equation [1a].

$$\lambda\ (c, C, K, L, M, S) = 0 \quad [2]$$

In equation [2], λ denotes a transformation relation, and c represents a vector of computer characteristics. Equation [2] thus says that the output of the computer manufacturer is the *joint production* of units of speed, memory and so forth, rather than simply the number of machines produced. This view of things is firmly grounded in engineering considerations. For example, during the heyday of the mainframe computer, engineers within computer manufacturing companies routinely spoke of computer output in terms such as "shipping MIPS" (MIPS is a measure of computer speed). I leave the number of computers, C, in equation [2] to admit the possibility that the costs of the computer manufacturer depend on the number of computer "boxes" produced, as well as on the characteristics of the boxes, perhaps for scale economy considerations.

A problem immediately arises with equation [2]. Though the quality of computer output is represented, in the form of computer characteristics, c, the semiconductor input to the manufacture of computers is entered as if only the number of semiconductors mattered, and not their characteristics. Engineering relationships that have become common knowledge tell us that the characteristics of semiconductors (density and so forth) account for a large part of the improvement in computer performance. In turn, we also know that the characteristics of semiconductor manufacturing equipment (resolution and so forth for steppers) account for the miniaturisation that is at the root of improved semiconductor performance.

Accordingly, a chain of characteristics must be considered in this model. I thus rewrite equations [1a-1c] in terms of the characteristics produced at one stage and used as inputs in another – see [3a-3c]. In all cases, I follow the convention of using lower case letters to represent the characteristics of the output or input designated with the corresponding capital letter. For the purposes of this analysis, the K, L, M variables are assumed homogeneous.

$$\lambda\ (c, C, K, L, M, s, S) = 0 \qquad [3a]$$

$$\psi\ (s, S, e, E, c, C, L, M) = 0 \qquad [3b]$$

$$\zeta\ (e, E, K, L, M) = 0 \qquad [3c]$$

Beginning with equation [3c], the characteristics of semiconductor manufacturing equipment (e), and the number of machines (E), specify the heterogeneous output of that industry. In turn, the characteristics of the equipment and the number of machines (e, E) provide part of the capital input to the semiconductor industry (equation [3b]); the other part consists of computer characteristics and the number of computers (c, C). In sequence, the characteristics that define the output of the semiconductor industry (s) also define productive inputs (s, S) into the computer industry (equation [3a]).

I assume that capital services are proportional to capital goods, which implies that the quantity of characteristics produced as the output of the capital goods producing industry defines the quantity of the services of characteristics of those capital goods in the using industry. Specifically, I assume that the characteristics of a capital good all decay at the same rate.[1]

I next introduce hedonic measures into the model. It is well known that a hedonic function is a relation between the price of the good and the quantities of characteristics the good contains. Thus,

$$P_S = h_s\ (s) \qquad [4]$$

for example, is a hedonic function for semiconductor characteristics, where P_S is a vector of the prices of semiconductors with various capabilities, defined by the vector of characteristics quantities, s.

At this point, there is no hedonic function explicitly in equations [3a-3c]. However, Rosen (1974) shows that the price of a semiconductor characteristic, say, is determined by the demand for the characteristic from the users (among the users is the computer industry), and the supply or cost conditions of the suppliers. In general, each buyer has a different demand function and each seller has a different cost function.[2] The hedonic function is formed from an envelope of those characteristics' demand and supply functions for individual buyers and sellers – see Rosen (1974), or Triplett (1987) for a concise restatement.

Thus, several hedonic functions are formed by the interaction of demands and supplies of using and supplying industries in the model of [3a-3c].[3] The hedonic function for semiconductor manufacturing equipment (stepper) characteristics depends on the distributions of stepper producers' cost functions and stepper buyers' demand functions. The hedonic function for semiconductor characteristics is determined in the same way by the distributions of buyers and sellers of semiconductors. The hedonic function for computer characteristics is determined partly by computer users' (most of whom are not explicitly in the model) demands for computer characteristics, and the producers' cost functions for computer characteristics. The three hedonic functions, for computers, for semiconductors, and for semiconductor manufacturing equipment, respectively, are:

$$P_C = h_C\,(c) \qquad [5]$$

$$P_S = h_S\,(s)$$

$$P_E = h_E\,(e)$$

There are no empirical implications to [3a-3c], or to [5], unless we know what the characteristics are. Because the relations in [3a-3c] contain quantities of characteristics, we must be able to count the quantities of characteristics produced and consumed. If we rewrite [3a-3c], using production duality theory, in terms of the costs of producing equipment, semiconductors, and computers, we must also know or be able to estimate the prices of the characteristics. Or, putting it another way, since we will probably in practice measure the outputs and inputs of these high-tech goods by deflating values of shipments, we must be able to determine the quantities of characteristics in the shipments data as well as the characteristics' prices for the deflation approach to work. Indeed, determining what the characteristics are, and obtaining data to measure them and to estimate their prices, is a major empirical endeavour.

Notice, however, what the model says about the characteristics. First, they are costly to produce. If e, say, were not costly to produce – that is, if a stepper with a higher degree of resolution did not cost more to produce than a stepper with lower resolution capabilities – then ξ (.) would be unaffected by the levels of the elements in e, and e would therefore drop out of [3c]. Putting this another way, if the utilisation of K, L, and M inputs in the semiconductor manufacturing equipment industry were fully accounted for by output measured simply as the count of machines produced (E), then enumerating the characteristics of those machines (e) – that is, their quality – would be redundant for the analysis of production and of production cost in the semiconductor equipment manufacturing industry. A similar argument applies to characteristics vectors s and c in their respective producing industries.

A further implication is that the characteristics must be productive for the user. If, say, the elements in the vector e were not productive in the semiconductor industry – that is, if steppers with higher degrees of resolution did not affect the output of the semiconductor industry – then the elements in the vector e would not enter the relation Ψ (.), and e would drop out of the production function for semiconductors. A similar argument applies to the characteristics vectors s and c their respective using industries.

Though I do not wish to minimise the difficulties in implementing an empirical hedonic study, some criticisms of hedonic price indices amount to the assertion that we cannot know the characteristics. Engineering information tells us the characteristics that affect the production cost of, say, steppers, as well as the stepper characteristics that are important in the production of semiconductors. The information we need about the characteristics of steppers is obtainable in principle from knowledge of the two production processes, the one for steppers and the one for semiconductors. One cannot carry out a sensible hedonic study without technical knowledge of how the product is produced and how it is used.[4] Some criticisms of hedonic methods arise because economists do not take seriously enough the concept of an engineering production function. I have written on this elsewhere (Triplett, 1985).

I emphasize that the model developed here applies much more broadly to the problem of measuring outputs and inputs for productivity measurement. It is not only a capital goods model. For example, measures of labour quality for productivity measurement normally make use of the well-known human capital model of labour economics; the costly acquisition of human capital by workers, and its productive utilisation by employers, are both illustrations of the hedonic hypothesis (where education, experience and other skills are characteristics of labour). Moreover, building human capital into the labour inputs contained in [1a-1c] by the procedures followed by Jorgenson, Gollop and Fraumeni (1987), and in the excellent implementation of the human capital model in US Bureau of Labor Statistics productivity measures (see US Bureau of Labor Statistics, 1993), are labour market applications of hedonic functions.

It is not necessary to explore here a number of issues that have arisen in the hedonic price index literature. I myself have made the distinction between "input characteristics" and "output characteristics", primarily in the context of an acrimonious and rather confused dispute in the 1970s over the proper interpretation of hedonic indices, and their employment in national accounts and productivity measures (see Triplett, 1983). I now regard this old issue as settled on the basis of my 1983 article. Although the distinction between input and output characteristics is theoretically interesting, it does not, I believe, have an empirical application to the present discussion. I have implicitly assumed it away by specifying that the characteristics of semiconductor output, say, are the same as the semiconductor characteristics inputs into the computer production process. Empirically, I do not believe there is any technical question that this is true.

Consider now any of the output measures in [3a-3c]. Each of these output measures is a function of the number of units and the number of characteristics per unit. For example, the output of computers is described by the numbers of computers of all types (C) and the quantities of each of the characteristics (c) that each computer type contains.

There are two ways to look at this, both leading to roughly the same thing. On the one hand we can think of the output of the computer industry, say, as the total quantity of characteristics produced – that is, multiplying the number of machines by the memory size per machine yields a quantity of computer memory, measured in units such megabytes. The output of the computer industry under this way of looking at it is a vector of quantity measures for characteristics, such as memory size, speed and so forth. We can combine the vector of characteristics into a measure of the total output of the computer industry by constructing a real quantity index number, composed of units of the characteristics speed, memory size and so forth, where the characteristics' quantities are weighted in some manner by prices of characteristics. The corresponding price index for the output of the computer industry is an index number that is made up from the prices of the characteristics, weighted by characteristics' quantities. Because this price index uses prices and quantities of characteristics, it can be thought of as a hedonic price index.

Alternatively, we can think of each of the different types of computer as a separate "good." We can think of the price of each of these computer types as indicating the value of the characteristics bundled into each computer – that is, the price of a computer is the revenue from the sale of the bundle of characteristics contained in it (so the computer price is a function of characteristics' prices and quantities). On this way of looking at it, the real quantity index of computers weights outputs of these different computer types with their different prices, and the price index for computers is a more or less a normal price index composed of computer prices, weighted by the numbers of computers of each type.[5] Because this price index makes use of quantities of characteristics in demarcating different computer types, and will also in practice use the prices of characteristics to "adjust" for changes in characteristics' quantities (that is, as "quality" adjustments), this price index can also be thought of as a hedonic price index.

In either case, we must estimate a hedonic function, and compute a hedonic price index of one form or another. It does not much matter how we use information from the hedonic function. We might use it to "adjust" the prices and quantities of individual computers, and so remain in the conventional world of prices and quantities of "goods"; or we might interpret the hedonic price index as a price index for computer characteristics, to be used with a quantity index that is also composed of computer characteristics.[6] In the latter case, the quantity index shows the total quantity of computer characteristics produced, without explicit reference to the quantities of computer "boxes". It seems somewhat easier for economists to think of "quality-adjusted" prices and "quality-adjusted" quantities of goods; on the other hand, it can be valuable to free our thinking from dependence on conventional "goods" notions and to use the concepts of characteristics' quantities and characteristics' prices directly. An example of the latter approach to constructing characteristics' price and quantity indices is Triplett (1983).

Inter-industry productivity

Productivity as conventionally defined is the ratio of outputs to inputs.[7] It may be thought of as a shift in one of the production functions in [3a-3c], in which case productivity is a measure of technical change. As noted above, it does not much matter whether we think of the shifts in [3a-3c] as shifts in production functions that contain "quality-adjusted" quantities (and prices) of goods, or whether we think of the shifts in [3a-3c] as shifts in production functions defined on output and input characteristics (such as s or c). It is, however, important that the characteristics are explicitly *built into* [3a-3c] and not tacked on as *ad hoc* "adjustments".

Note that "quality change" in [3a-3c] – a change in the quantities of characteristics, per unit of goods – is not necessarily in itself a productivity change. Quality change is endogenous to the model of [3a-3c], so the quantity of characteristics per unit can change *without* a shift in [3a-3c]. When the characteristics are omitted from the model, as in equations [1a-1c)], such changes in characteristics per unit may be perceived, incorrectly, as a shift in the production function.

A very useful alternative way to think about productivity is to conceive of it as a shift in the cost function, or as the ratio of output prices and input prices. If input prices grow more rapidly than output prices, for example, it must either be that profit margins are compressed or that producers have become more efficient. To my knowledge, the first proposal to compute productivity from input and output price indices is Copeland and Martin (1938).

Corresponding to each of the production functions in [3a-3c] is a production cost function showing the cost of producing, respectively, computers, semiconductors, and semiconductor manufacturing equipment. In the usual way, these cost functions are dual to the production functions, and they have as arguments the prices of the productive inputs, including the prices of the characteristics.

$$B_C = B_C (P_K, W, P_M, p_S) \quad [6a]$$

$$B_S = B_S (p_E, p_C, W, P_M) \quad [6b]$$

$$B_E = B_E (P_K, W, P_M) \quad [6c]$$

In [6a-6c], B_i indicates the total cost of producing the output of industry i, W is the price of the labour input, P is the price of a good, p designates a characteristics' price or prices, and the symbols for the subscripts have already been defined.[8]

For time series or for international comparisons, we specify the prices as index numbers, where the form of each index number depends on the form of the cost function, or of a sub-function of the cost function. In each of our high-tech industries, the output price index is a hedonic price index.[9] Moreover, the hedonic price index of the supplying high-tech industry appears among the price indices for the using industry's inputs.

Suppose that the aggregator across the input price indices in [6a-6c] is a Cobb-Douglas cost function. Thus, for the computer industry, for example, we have:

$$\text{In } B_C = \sum a_i \text{ In } P_i \quad [7]$$

where the i input prices (i=1, ..., 4) are the prices of the K, L, M, and S inputs in [6a], and α_i is the share of input i in total costs. For the Cobb-Douglas case,

$$\Delta B_C/B_C = \sum a_i (\Delta P_i/P_i) \quad [8]$$

the rate of change in cost is a share-weighted sum of the rates of change in input prices. Continuing with the computer example, the change in productivity (π_C) is then:

$$\Delta\pi_C/\pi_C = (\Delta P_C/P_C) - (\Delta B_C/B_C) \quad [9]$$

where the two terms on the right-hand side are rates of growth in product price and in input costs.

The full implementation of a productivity calculation based on input and output prices requires information on all the input prices, and enough additional information about the cost function to compute an input cost index.[10] To reduce the information required on input costs, I now make use of an assumption introduced earlier. In [3a-3c)], I specified that all labour inputs, capital inputs (except for semiconductor manufacturing equipment capital and computer equipment capital supplied to the semiconductor industry), and materials inputs (except for semiconductors supplied to the computer industry) were undifferentiated among the three high-tech industries. That assumption is of course unlikely to be valid. However, we can motivate it in the context of [6a-6c], where the equivalent assumption is that the price indices for labour (W), for example, move together regardless of the purchasing industry. Though labour composition is unlikely to be exactly the same for all industries, to assume that changes in wages paid by all three industries are dominated by the general trend of wages does not seem unreasonable. Similarly, I assume that the prices of materials, energy and so forth to the three industries move with general prices of materials, energy and so forth. This implies that price indices for general capital, except semiconductor manufacturing equipment and computer equipment (that is, P_K), and for materials, except semiconductors (that is, P_M), and for W are the same regardless of the using industry.

Suppose, for example, that in equation [8] all of the prices, other than the prices of the high-tech semiconductor inputs, remain fixed. Then the hedonic price index for semiconductor inputs to the computer industry will affect the production cost for the output of the computer industry in proportion to the share of semiconductors in computers. Then,

$$\Delta B_C/B_C = \alpha_S\ (\Delta P_S/P_S),\ \Delta P_i/P_i = 0 \text{ for all } i \neq s. \qquad [8a]$$

where α_s is the share of semiconductors in computers and $(\Delta P_S/P_S)$ is the price index for semiconductors. To illustrate, suppose that the share of semiconductors in computer cost is 20 per cent. Now suppose that the hedonic price index for semiconductors falls by 10 per cent. The effect of semiconductor price reductions on computer *costs* is thus 2 per cent (.20 x .10). If computer prices also fall 10 per cent, then we can say that productivity improved in the computer industry by approximately 8 per cent, the excess not accounted for by the decline in the industry's input price (see equation [9]). If computer prices fell only 1 per cent under the same circumstances, we would infer that productivity in the computer manufacturing industry declined by 1 per cent.

Of course the prices of labour, other capital and other materials will not be exactly constant. We can still use the same technique, only the productivity measures we obtain can be interpreted as relative productivities, the productivity change in the computer industry relative to the productivity change in the other two industries in our high-tech sector.

We can rewrite rates of change in the three Cobb-Douglas cost functions corresponding to [6a-6c] in terms of high-tech inputs and other inputs:

$$\Delta B_C/B_C = \alpha_S\ (\Delta P_S/P_S) + [\Sigma\alpha_i\ \Delta P_i/P_i,\ i \neq S] \qquad [10a]$$

$$\Delta B_S/BS = \alpha_E\ (\Delta P_E/P_E) + \alpha_C\ (\Delta P_C/P_C) + [\Sigma\alpha_i\ \Delta P_i/P_i,\ i \neq C, E] \qquad [10b]$$

$$\Delta B_E/B_E = [\Sigma\alpha_i\ (\Delta P_i/P_i)] \qquad [10c]$$

The estimated rates of change in the prices inside the square brackets are assumed common to all three industries. The estimates of cost change for this chapter exclude the prices inside the square brackets. This means that the estimated cost changes for the three industries are relative changes (the unknown cost changes for the semiconductor manufacturing equipment industry is the numeraire). Thus, when the estimated cost changes (excluding the square bracket terms) are used to compute productivity change, the productivity estimates are also relative, with the semiconductor manufacturing equipment industry as the numeraire:

$$\Delta\pi_C/\pi_C = (\Delta P_C/P_C) - (\Delta B_C/B_C) \qquad [11a]$$

$$\Delta\pi_S/\pi_S = (\Delta P_S/P_S) - (\Delta B_S/B_S) \qquad [11b]$$

$$\Delta\pi_E/\pi_E = \text{numeraire} \qquad [11c]$$

The data

Computer equipment price indices

The Bureau of Economic Analysis (BEA) introduced hedonic price indices for mainframe computers and for major items of peripheral equipment in 1985. See Cole *et al.* (1986), for the estimates, Cartwright (1986), for the details of the implementation, and Dulberger (1989); these studies and other research on computers and peripheral equipment are reviewed in Triplett (1989), which also discusses the research issues that arise in constructing hedonic indices for high-tech industries such as computers. A BEA price index for personal computers was introduced subsequently. Sadée (1996) documents the recently revised BEA computer equipment price indices that are summarised in Table 1. As indicated in Table 1, these price indices extend historically nearly to the introduction of these various types of computer equipment.[11]

Table 1. Price indices for domestic computer equipment

1992 = 100

	Mainframes		PCs[1]		Storage devices				Printers and other peripherals		Terminals	
					Disk drives[2]		Tape drives					
Year	Index	% change	Index	% change	Index	% change	Index	% change	Index	% change	Index	% change
1958	142 773.6				37 044.5		3 028.9		6 498.4		11 658.5	
1959	122 464.3	-14.2			19 854.8	-46.4	3 034.3	0.2	6 212.5	-4.4	11 145.7	-4.4
1960	90 140.8	-26.4			19 750.3	-0.5	3 741.8	23.3	5 678.7	-8.6	10 188.0	-8.6
1961	68 263.1	-24.3			18 914.3	-4.2	3 513.6	-6.1	3 770.1	-33.6	6 764.0	-33.6
1962	49 721.5	-27.2			12 069.6	-26/2	2 519.2	-28.3	2 173.2	-42.4	3 898.8	-42.4
1963	37 990.6	-23.6			9 796.8	-18.8	1 851.3	-26.5	1 516.0	-30.2	2 719.9	-30.2
1964	28 886.5	-24.0			9 158.6	-6.5	1 709.9	-7.6	1 261.6	-16.8	2 263.4	-16.8
1965	20 765.4	-28.1			7 889.7	-13.9	1 590.0	-7.0	1 093.8	-13.3	1 962.2	-13.3
1966	7 869.6	-62.1			6 866.5	-13.0	1 494.5	-6.0	1 105.2	1.0	1 982.7	1.0
1967	5 570.1	-29.2			4 785.8	-30.3	1 371.5	-8.2	1 084.7	-1.9	1 946.0	-1.9
1968	5 034.0	-9.6			3 269.6	-31.7	1 149.0	-16.2	1 037.0	-4.4	1 860.4	-4.4
1969	5 018.0	-0.3			2 467.7	-24.5	975.0	-15.1	971.1	-6.4	1 742.2	-6.4
1970	4 829.1	-3.8			1 909.7	-22.6	825.7	-15.3	936.0	-3.6	1 679.3	-3.6
1971	3 750.4	-22.3			1 430.0	-25.1	550.1	-33.4	836.2	-10.7	1 500.3	-10.7
1972	3 067.3	-18.2			1 034.1	-27.7	426.1	-22.5	781.3	-6.6	1 401.8	-6.6
1973	3 268.6	6.6			895.0	-13.5	299.5	-29.7	732.2	-6.3	1 401.2	-0.0
1974	2 780.3	-14.9			746.0	-16.6	132.1	-55.9	772.1	5.4	1 350.2	-3.6
1975	2 687.0	-3.4			660.2	-11.5	109.3	-17.3	706.0	-8.6	1 262.7	-6.5
1976	2 457.0	-8.6			474.3	-28.2	83.2	-23.9	538.8	-23.7	1 162.4	-7.9
1977	1 930.0	-21.4			379.9	-19.9	110.7	33.1	574.3	6.6	1 161.4	-0.1
1978	972.3	-49.6			295.3	-22.3	131.0	18.3	565.0	-1.6	1 062.4	-8.5
1979	797.6	-18.0			242.3	-17.9	114.0	-13.0	515.2	-8.8	846.3	-20.3
1980	550.4	-31.0			202.4	-16.5	106.2	-6.8	523.9	1.7	768.6	-9.2
1981	453.4	-17.6			191.3	-5.5	128.7	21.2	412.3	-21.3	737.7	-4.0
1982	382.5	-15.6	578.7		174.8	-8.6	133.9	4.0	403.3	-2.2	748.2	1.4
1983	348.2	-9.0	405.6	-29.9	139.0	-20.5	139.0	3.8	282.9	-29.9	683.0	-8.7
1984	251.4	-27.8	349.8	-13.8	113.3	-18.5	113.3	-18.5	293.3	3.7	559.0	-18.2
1985	185.7	-26.1	327.5	-6.3	113.1	-0.2	113.1	-0.2	341.1	-17.8	479.9	-14.2
1986	168.2	-9.4	241.3	-26.3	106.8	-5.6	106.8	-5.6	216.9	-10.0	379.6	-20.9
1987[3]	144.9	-13.9	217.6	-9.8	104.5	-2.2			168.0	-22.5	246.6	-35.0
1988	137.3	-5.2	199.1	-8.5	99.6	-4.7			146.2	-13.0	239.8	-2.8
1989	119.8	-12.7	185.2	-7.0	101.6	2.0			144.8	-1.0	196.5	-18.1
1990	106.3	-11.3	155.1	-16.3	105.8	4.1			135.1	-6.7	157.2	-20.0
1991	102.9	-3.2	130.8	-15.7	104.0	-1.7			114.5	-15.2	126.4	-19.6
1992	100.0	-2.8	100.0	-23.5	100.0	-3.8			100.0	-12.7	100.0	-20.9
1993	85.3	-14.7	78.7	-21.3	89.6	-10.4			94.3	-5.7	100.9	0.9
1994	80.1	-6.1	69.5	-11.7	78.0	-12.9			88.1	-6.6	93.5	-7.3

1. PC: Personal computers.
2. Direct access storage devices.
3. Beginning with 1987, tape drives and disk drive indices are not available separately. They have been combined to create the storage devices index.

Source: Sadée (1996).

The price indices for computer equipment in Table 1 have been constructed from different source data by several somewhat different methods.

The mainframe index for 1972-82 is the original IBM-BEA hedonic index (Cole *et al.*, 1986), as are the disk drive, tape drive, printer, and terminals indices. All of these indices are hedonic indices, and in all but one case, they implement the hedonic method in the same way: a hedonic function (equation [5], above) is used to impute a price when a particular computer model is present in one year of the sample period but is missing from another. Where a particular computer model is present in both years for which an index is computed, no imputation is required, and accordingly no use of the hedonic function is necessary. We might refer to this methodology as "matched model with hedonic imputation of missing prices". Moreover, for computers, each model is weighted in the price index with its own quantity sold, originally in a Paasche formula price index to match the implicit deflators then used in the US accounts.

For the years 1982 forward, BEA has updated the samples, re-estimated the hedonic regressions, and computed the price indices using the same methodology. With the last (1996) benchmark revision, Fisher chain indices for mainframes were computed, using as weights shipments data by specific model of computer.

The tape drive and disk drive indices are combined after 1987, partly because of the historic replacement of tapes as auxiliary storage media by disks. In the case of printers, different types of computer printers have shown quite different price movements. BEA now maintains separate price indices for dot-matrix, ink-jet, line printers and laser-type page printers. These are combined into an index for all printers using the chain Fisher formula now used in the US national accounts.

Beginning in 1994, the annual changes in all of the BEA price indices for computer equipment are taken from the corresponding components of the computer equipment price indices published by the US Bureau of Labor Statistics in the Producer Price Indices (PPI). Quarterly changes in the indices in Table 1 have also been moved by PPI indices since 1990.

The PPI indices for computer equipment are also hedonic price indices, though they use the hedonic methodology in a slightly different way. As in the BEA price indices, no use is made of the hedonic function for cases where an item of computer equipment is unchanged between two periods. However, when there is a change in the characteristics of a piece of computer equipment that appears in the Producer Price Index, a hedonic function is typically used to make a quality adjustment to account for the change in specification. The PPI methodology is based on the methodology introduced in Triplett and McDonald (1977). One might describe the PPI computer equipment indices as "matched model with hedonic quality adjustments."

The BEA computer equipment indices before 1972 are mostly derived from the review of earlier research studies in Triplett (1989, Tables 4.6A and 4.11). This same reference includes indices for mainframe computers extending back to 1953 (the introduction of the commercial computer) and peripheral equipment indices also extending into the 1950s. These indices combine results from research studies, a number of which were published in the computer science literature. For the most part, the methodology of the computer science studies resembles hedonic studies that compute the price index by insertion of time dummy variables into a hedonic function run on several years' data.

The BEA price index for personal computers does not make explicit use of a hedonic function. However, it controls the comparability of the observations in the samples by reference to the characteristics of the personal computer, and it introduces new models into the index in the year in which they are first on the market.[12] Its rate of decrease is somewhat slower than the hedonic index for personal computers in Berndt and Griliches (1993).

Semiconductor price indices

In the benchmark revision of the US national accounts published just this year (*Survey of Current Business*, January-February, 1996), new price indices for MOS memory semiconductors and for microprocessor chips were introduced. These indices are shown in Table 2. They are the work of Grimm (1995), building on earlier research by Dulberger (1993) and Flamm (1993) for memory chips, plus original research on logic chips.

In the seven price indices for memory chips,[13] the unit of measurement was the price per kilobyte of memory on the chip. Over the interval 1977-92, prices of all seven types of memory chips declined extremely rapidly. Average annual rates of price change ranged from -19 to -45, with DRAM's, the dominant memory chip used in computers, dropping about 34 per cent per year. As Table 2 shows, price declines for memory chips slowed after the US-Japan semiconductor accord in the mid-1980s, and slowed again in 1993 and 1994.

Table 2. World-wide semiconductor price indices and BEA computer equipment price indices
1992 = 100

	(A) Memory chip	(B) Logic chip	(C) Semiconductors[1]	(D) Domestic computer equipment
1974	177 837	-	204 209.2	1 710.7
1975	56 057	-	64 369.9	1 583.0
1976	34 362	-	39 457.7	1 321.1
1977	19 923	-	22 877.5	1 149.3
1978	11 668	-	13 398.3	774.1
1979	9 733	-	11 176.3	640.7
1980	6 897	-	7 919.8	499.7
1981	3 348	-	3 844.5	438.5
1982	2 073	-	2 380.4	391.6
1983	1 513	-	1 737.4	326.0
1984	1 186	-	1 361.9	263.4
1985	557	722.2	639.6	223.3
1986	363	488.5	424.7	193.7
1987	332	426.0	379.0	167.1
1988	387	375.8	381.4	155.1
1989	329	280.4	304.7	144.4
1990	183	187.0	185.0	129.7
1991	130	152.5	141.3	116.2
1992	100	100.0	100.0	100.0
1993	94	69.5	81.7	86.0
1994	94	43.9	69.0	77.7

1. Equally weighted average of columns (A) and (B), extended backward from 1985 by column (A).
Source: For semiconductor price indices, Grimm (1995); for computer equipment, Sadée (1996). Grimm produced price indices for seven different types of memory chips and two types of microprocessor chips.

Because of the data set available, these price indices are world-wide price indices, not price indices specifically for semiconductors sold in the US market. However, semiconductors have a world market, and except for short-run changes, prices of chips in the US market probably move quite closely with world market prices. The major exception was probably the period of the US-Japan semiconductor agreement, which raised US prices of memory chips relative to those on world markets.

The procedures used by Grimm for memory chips were patterned on those of Dulburger (1993). Earlier years' data for two types of memory chips were obtained from Dulberger, and other data were obtained from a private consulting firm. These indices are not full hedonic indices, because information on some of the price-determining characteristics was not available. One can think of the average price per bit measure used in the memory chip indices as a one-variable hedonic function, constrained to pass through the origin. As with similar estimates, it is not possible to tell whether adding additional performance variables to the hedonic function would have raised or lowered the estimated price changes.

Microprocessor, or logic, chips are the heart of modern personal computers. Grimm estimated hedonic price indices for Intel and Motorola microprocessor chips. As indicated in Table 2, these price indices also decline very rapidly, about 27 per cent per year on average since 1985.

For purposes of this paper I have averaged Grimm's memory chip index and his logic chip index because available data suggest that shipments of the two groups of semiconductors are about equal size. When better weights are available, an aggregate semiconductor index will be constructed by the Fisher formula.

Semiconductor manufacturing equipment (stepper) price index

Semiconductor manufacturing involves many different processes, and many different kinds of manufacturing machinery. A crucial process is alignment and exposure, the photolithographic process that reduces and transfers onto the surface of a silicon wafer the electronic circuitry encoded in the semiconductor. The dominant type of aligning machinery is called a "stepper".

Lau and Liu (1996), in a preliminary study sponsored by BEA that is still not quite completed, collected price and characteristics data for steppers covering the period 1978-94. Because the price observations available are recorded primarily at the point of introduction of a new machine, the number of observations was somewhat limited, and as a result estimates of average annual price change over the period were considered more reliable than annual price indices.

In the preliminary results, it appears that the hedonic price index is sensitive to aspects of the specification of the hedonic function. Three alternative estimates of trend stepper price indices appear in Table 3. However, all of the specifications show that the price of steppers, corrected for performance, has been rising through the 1978-94 period. Thus, high-tech semiconductor manufacturing equipment does not show the rapidly declining prices of the semiconductors that use it, nor of the computers that are the consumers of the semiconductors.

Table 3. Alternative estimates of price change for semiconductor manufacturing equipment (steppers)

Average annual rates of change, 1978-94

Semilog, "traditional"[1]	4.7%
Semilog, "frontier"[2]	3.4%
Translog[3]	6.0%

1. Semilog functional form, price index computed from time trend variable.
2. Two-stage estimation method, to allow for effects of "best" characteristics available on the market.
3. Translog functional form, price index computed from time trend variable.

Source: Lau and Liu (1996).

I use the middle of these estimates in the calculations in this chapter, without necessarily implying that it is the best measure of price change for steppers.

Input cost shares

The productivity computations also require shares in input costs accounted for by the high-tech inputs. Input cost shares are less readily available than might be expected.

The semiconductor industry. For the semiconductor manufacturing industry, high-tech inputs are capital goods – computer equipment, and semiconductor manufacturing equipment.[14] Two sources provide investment to output ratios. The investment/output ratio is not the same thing as the share of semiconductor equipment capital in total semiconductor production cost, because investment is not capital stock, and capital stock is not capital services. However, at present, only investment to output ratios have been estimated.

Table 4. Shipments, capital expenditures and shares for the semiconductors and related devices industry
SIC 3674

	1977 US$ million	1982 US$ million	1987 US$ million	1992 US$ million
Value of Shipments (VOS)[1]	5 322.6	12 429.9	19 794.9	32 157.0
New capital expenditures[2]	409.0	1 741.9	1 940.2	3 156.6
Buildings and other structures[3]	60.8	468.5	240.4	378.9
Machinery and equipment[4]	348.2	1 273.5	1 699.8	2 777.7
A. Autos, trucks etc.[5]	2.1	2.5	3.0	0.4
B. Computers and peripherals[6]	11.7	120.9	190.3	229.8
C. All other[7]	315.2	1 042.6	1 506.4	2 547.5
D. n.s.k.[8]	19.2	107.4	-	-
Computers & peripherals / VOS	0.22%	0.97%	0.96%	0.71%
All other / VOS	5.92%	8.39%	7.61%	7.92%

1. Value of shipments, all years: Table 1a (1992).
2. All years: New capital expenditures (Table 1a, 1992); plus (electronic computing equipment, for the years 1982, 1987, and 1992, Tables 7 in (1982), (1987) and (1992).
3. New buildings and other structures from Tables 3a (1977 and 1982) and Tables 3b (1987 and 1992).
4. New machinery and equipment from Tables 3a (1977 and 1982) and Tables 3b (1987 and 1992); plus electronic computing equipment, Tables 7 (1982, 1987, and 1992) for the years 1982, 1987 and 1992. For 1977 and 1982, Machinery and equipment detail is based on sample estimates; proportions from the sample were applied to Census control totals.
5. Automobiles, trucks, etc., for highway use, from Table 3b (1977), Table 3d (1982) and Tables 3c (1987 and 1992).
6. Computers and peripheral data processing equipment, from Table 3b (1977), Table 3d (1982), Tables 3c (1987 and 1992); plus electronic computing equipment, for years 1982, 1987 and 1992 from Tables 7 (1982, 1987, 1992).
7. All other, from Table 3b (1977), Table 3d (1982), Tables 3c (1987 and 1992).
8. New machinery and equipment, n.s.k., from Table 3b (1977), and Table 3d (1982). Represents total machinery and equipment expenditures for establishments that did not break down their expenditures by specific type. Not reported in 1987 and 1992.

Source: Census of Manufactures, Industry Series, MC77-I-36E, Electronic Components and Accessories (1977); MC82-I-36E, Electronic Components and Accessories (1982); MC87-I-36E, Electronic Components (1987); MC92-I-36E, Electronic Components (1992).

The US Census of Manufactures reports new capital expenditures for the semiconductor industry (SIC 3674). As shown in Table 4, expenditures on new machinery and equipment are divided into three categories – vehicles, computer equipment, and "all other". New computer equipment investment amounts to under 1 per cent of semiconductor value of shipments.

The "all other" machinery and equipment category includes semiconductor manufacturing equipment, and other equipment that is not, strictly speaking, high-tech. Nevertheless, in the absence of more detailed information, I take the entire "all other" category as investment in semiconductor manufacturing equipment. On this basis, the share of semiconductor manufacturing equipment investment is around 7-8 per cent of industry value of shipments (Table 4), which for the reasons noted ought to be an overstatement.

The second source is VLSI Research, Inc., which reports the ratio of *world-wide* investment in semiconductor manufacturing equipment to semiconductor output. As shown in Table 5, the world-wide share of equipment investment (15 per cent in 1992) is substantially greater than the USshare computed from the Census of Manufactures (8 per cent in 1992).

Table 5. Comparison of investment/output ratios for the semiconductor industry
Percentages

	1977	1982	1987	1992
Semiconductor manufacturing equipment to semiconductor output				
Census of Manufactures (US)[1]	5.9	8.4	7.6	7.9
VLSI Research Inc. (world-wide)[2]	7.7	14.0	12.8	15.0
Plant & equipment (P&E) to semiconductor output				
Census of Manufactures (US)[3]	7.7	14.0	9.8	9.8
Flamm US4	n.a.	14-15	14-15	14-15

Source:
1. Table 4.
2. VLSI Research, Inc., "Diffusion Rates".
3. Computed from Table 4.
4. Flamm (1996), Figure 1-3, p. 15.

Additional information appears in Flamm (1996). From industry sources, Flamm graphs trends in US semiconductor plant and equipment (P&E) expenditures, as a share of output. Though the P&E share fluctuates from year to year, for the Census years 1982, 1987 and 1992 the share was about the same, roughly 14-15 per cent. The Census of Manufactures also reports P&E expenditures (see Table 4) and the P&E share is calculated in Table 5. The census share declines from 14 per cent for 1982 (about the same as Flamm's figure) to substantially lower shares for 1987 and 1992 (around 10 per cent), whereas Flamm's data show no decline. Although shares fluctuate in all the data that are available annually, fluctuations do not account for the differences tabulated in Table 5.[15]

Thus, available information suggests either that the US semiconductor manufacturing equipment investment share is lower than that of other countries; that the US Census of Manufactures estimate is low for US semiconductor producers; or both.

Because the US industry specialises in the highest end of the technology, one might think that, other things equal, the US industry's investment share would be higher than that of other countries. For example, Flamm (1996) notes that capital, as a share of direct manufacturing cost, rose from 15 per cent in the 1970s to roughly 60 per cent in the 1990s, for the highest-technology chips. On the other hand, the US industry's production is also far more R&D-intensive than those of other countries, other than perhaps Japan, which means that direct manufacturing cost is a lower proportion of total cost. Accordingly, the importance of R&D tends to reduce the US capital share in value of shipments.[16]

In the calculations in the following section, I use both the Census of Manufactures estimate and the VLSI Research, Inc. estimate in alternative estimates of semiconductor industry productivity.

The computer industry. In the computer industry, high-tech inputs are semiconductors.[17] Determining the share of semiconductor inputs in computer costs is also difficult. The 1987 US input output table shows a share of approximately 14 per cent. Very little data on the computer industry's use of semiconductors appears in Census of Manufactures for 1987 and before.[18]

Although more information on purchased electronic components appears in the 1992 US Census of Manufactures, determining the share of semiconductors in computer manufacturing using 1992 Census data is complicated by the fact that many semiconductors are first assembled on boards, and the purchased input data in the Census of Manufactures record the boards and various semiconductors in a way that is not easy to disentangle.[19] For reasons given below, it seemed preferable to be overly inclusive in classifying purchased inputs. Accordingly, in Table 6, all identifiable inputs that could contain semiconductors or are semiconductor-related (including some resistors and other devices that are probably not properly semiconductor inputs) are added together.

Table 6. 1992 Value of shipments, semiconductor inputs and shares in computer equipment industries (SIC 3571, 3572, 3575, and 3577)

US$ million

	SIC 3571 Electronic computers	SIC 3572 Computer storage devices	SIC 3575 Computer terminals	SIC 3577 Printers (computer peripheral equipment nec)	Total computer equipment
Value of Shipments (VOS)	38 205.9	9 544.3	2 070.7	12 156.5	61 977.4
Cost of materials (delivered cost)	21 388.9	4 991.7	1 288.2	7 166.4	34 835.2
Semiconductors and related devices[1]	6 677.9	567.4	428.0	1 717.5	9 390.8
Ratio semiconductors / VOS	17.5%	5.9%	20.7%	14.1%	15.2%

1. Semiconductors and related devices has been estimated by summation of the following Census of Manufactures input codes:
   367201 printed circuit boards (without inserted components)
   367408 semiconductors, including transistors, diodes, rectifiers, and integrated circuits
   367980 memory boards
   367983 peripheral controllers (graphics boards, drive controller, etc.)
   367984 computer processors (system boards, array processors, etc.)
   367985&6 communications boards (LAN boards, D/A and A/D converters, etc.)
   367987 other boards
   367501 capacitors for electronic circuitry
   367601 resistors for electronic circuitry
   367800 connectors for electronic circuitry
   Estimates for disclosures and allocations of "n.s.k." (the totals for establishments that did not report detailed materials data) have been supplied by Belinda Bonds and William McCarthy of BEA's input-output staff, using standard I-O estimating methods.

Source: 1992 Census of Manufactures, Industry Series, MC92-1-35F, Office and Computing Machines. Tables 1a (Historical Statistics), 3a (Summary Statistics for the Industry), and 7 (Materials Consumed by Kind).

The implied share of semiconductors in computer equipment appears surprisingly low, especially so since, as noted, the calculation probably overstates the quantity of semiconductors that are really in the data. Note that the various items of computer equipment use semiconductors in different proportions (and they also use different types of semiconductors). For computers, the share of semiconductors is 17.5 per cent and for computer equipment as an aggregate, the share is 15.2 per cent.

Intuition, discussions with economists who have worked on computer and semiconductor industry issues, and the corroborating suggestions in the VLSI Research, Inc. data, all suggest that the

Census of Manufactures share may be low. In the following section, I also employ alternative shares, to provide a sensitivity test.

The results

In this section, I report relative industry productivities computed according to the model set out in the first section. The productivity of the semiconductor manufacturing equipment industry is the numeraire, so the semiconductor industry and computer industry estimates show the productivity of those industries relative to the unknown productivity of the semiconductor equipment manufacturing industry.

To compute the relative productivity of the semiconductor industry according to the model of described in the first section of this chapter, one needs the price of semiconductor output and of its high-tech inputs, specifically, semiconductor manufacturing equipment and computer equipment. The price movement of semiconductor manufacturing equipment is represented by the price movement of steppers. Prices for other semiconductor manufacturing equipment may move differently. However, alignment/exposure equipment (of which steppers are the dominant type) accounts for about 13 per cent of total investment in semiconductor manufacturing equipment in recent years (Lau and Liu, 1996), and steppers are the only semiconductor manufacturing equipment product that has been investigated.

Table 7. Relative industry productivity estimates for the semiconductor industry, 1978-94

Annual averages, or average annual rates of change

		1978-85	1985-94	1978-94
A.	Price change, semiconductor manufacturing equipment (SME)	4.7	4.7	4.7
B.	Share of SME in semiconductors	13.8	15.4	14.4
C.	Contribution, SME to semiconductor cost	0.65	0.72	0.68
D.	Price change of computer equipment	-16.27	-11.07-	13.38
E.	Share of CE in semiconductors	0.60	.84	0.72
F.	Contribution, CE to semiconductor cost	-0.097	-0.093	-0.096
G.	Contribution, SME and CE to semiconductor cost	0.55	0.63	0.58
H.	Price change of semiconductors	-35.25	-21.92	-28.06
I.	Relative semiconductor productivity	35.8	22.6	28.6

Source:

A: From Table 3, line 1.
B: Computed from annual "diffusion rates" published by VLSI Research, Inc.
C: Row (A) x row (B).
D: From Table 2, column D, average annual rates of change.
E: From Table 4. 1977 & 1982 average used for period 1978-1985, 1987 & 1992 average used for period 1985-94.
F: Row (D) x row (E).
G: Row (C) + row (F).
H: From Table 2, column C, average annual rates of change.
I: Difference in the growth rates: (Row (H) - row (G)) x (-1).

As Tables 3 and 7 show, the price of semiconductor manufacturing equipment has risen modestly, around 5 per cent per year over the period investigated. Because the share of semiconductor manufacturing equipment in semiconductor costs, based on VLSI Research, Inc. data, is only around 1:7 (Table 7, line B), the under 5 per cent increase in the performance-adjusted price of semiconductor manufacturing equipment translates into a less than 1 per cent contribution to increasing semiconductor costs (Table 7, line C).

Computer equipment purchased by the semiconductor industry has declined dramatically in price (Table 7, line D). However, its very small share in semiconductor costs (line E) means that computers make only a small, though negative, contribution to semiconductor costs (line F). Putting the cost effects for both types of high-tech equipment together, the effect of high-tech equipment on semiconductor costs is only around one-half of 1 per cent (actually, 0.58) for the period as a whole (Table 7, line G), and not appreciably different for the sub-periods.

As Table 7 also shows, the performance-corrected change in the price of the semiconductor industry's output has fallen dramatically, by nearly 30 per cent annually over the period investigated. Putting semiconductor producers' input cost increase (line G) together with the price decrease of their output (line H), one concludes that the relative productivity of the semiconductor industry has increased slightly more than its recorded price decline (Table 7, line I). Thus, for the entire 1978-94 interval, relative semiconductor productivity is estimated to have increased by over 28 per cent *annually*; it increased by over 35 per cent *annually* from 1978 to 1985, and by over 22 per cent *annually* from 1985 to 1994. Clearly, productivity increase in the semiconductor industry is prodigious by any measure.

As noted above, semiconductor manufacturing equipment shares computed from the Census of Manufactures are about half the shares recorded in Table 7. I recomputed semiconductor productivity using Census of Manufacturing shares.[20] The recomputation has the effect of lowering the already small "contribution" entry in Table 7, line C, and accordingly also lowering the combined contribution in line G. The productivity estimate for the semiconductor industry is not much changed (for example, it falls from 28.6 to 28.3 per cent for the 1978-94 interval).

I now turn to the calculation of the relative productivity of producing computers. Table 8 begins with the impressive rates of decline in the performance-corrected price of semiconductor inputs into the computer industry. As already documented in Table 2, these price declines average 22 per cent annually in the most recent period (1985-94); a rate that is actually lower than the decline recorded in the 1970s (nearly 50 per cent per year for 1974-78 – see Table 8).

As noted above, estimates of the share of semiconductors in computers are problematical. Column B1 of Table 8 records the 1992 Census of Manufactures' share from Table 6. Because this share estimate is relatively low (around 15 per cent), the contribution of semiconductors to computer equipment costs is also relatively modest, only a little over 3 per cent annually for 1985-94, for example, and a bit more than 4 per cent annually for 1978-94 (column C1).

Table 8. Relative industry productivity estimates for computer equipment, 1978-94

	(A)	(B1)	(B2)	(B3) :	(C1)	(C2)	(C3)	(D)	(E1)	(E2)	(E3)
	Price change, semiconductors	Share of semiconductors in computer equipment			Percentage contribution, semiconductors to computers			Price change, computer equipment	Relative computer equipment productivity		
Years		Census	Assumed shares		Census	Assumed shares			Census	Assumed shares	
1974-78	-49.4	15.2	30	45	-7.5	-14.8	-22.2	-18.0	10.5	3.2	-4.2
1974-84	-39.4	15.2	30	45	-6.0	-11.8	-17.7	-17.1	11.1	5.2	-0.7
1974-94	-32.9	15.2	30	45	-5.0	-9.9	-14.8	-14.3	9.3	4.4	-0.5
1978-85	-35.2	15.2	30	45	-5.4	-10.6	-15.9	-16.3	10.9	5.7	0.4
1985-94	-21.9	15.2	30	45	-3.3	-6.6	-9.9	-11.1	7.7	4.5	1.2
1978-94	-28.1	15.2	30	45	-4.3	-8.4	-12.6	-13.4	9.1	5.0	0.8

Source: Column (A): Average annual rates of change, computed from Table 2, column (C).
Column (B1): Table 6.
Columns (B2 and B3): Assumption.
Columns (C1, C2, C3): Column (A) times columns (B1, B2, B3).
Column (D): Average annual rates of change, computed from Table 2, column (D).
Columns (E1, E2, E3): Column (D) minus columns (C1, C2, C3) x (-1).

Because the price of computer equipment has been dropping in excess of 10 per cent per year (column D of Table 8), and more like 16-17 per cent per year in the 1970s and 1980s, computer prices are clearly falling more rapidly than what one would expect from the contribution of semiconductor price decreases to computer costs. As a result (Table 8, column E1), the computer industry's relative productivity, using the Census semiconductor share, improves around 9 per cent per year over the period studied.

However, the semiconductor input share is crucial to the computer productivity estimate. As noted above, there are reasons to believe that the semiconductor share in computer equipment manufacturing costs exceeds 15 per cent. Some industry sources suggest that it may be as high as 45 per cent. Microprocessor chips, memory boards, graphic boards or chips, communications boards and so forth, for example, are the essence of a modern personal computer. All are products of the semiconductor industry or related electronic components industries, and are inputs to the production of computers.

To provide sensitivity ranges, I recomputed computer industry productivity with assumed shares of semiconductors that are greater than the Census of Manufactures' share. As the logic of the calculation makes evident, the result of increasing the assumed semiconductor share is to increase the percentage contribution of semiconductors to reducing the production costs of computer manufacturing, and correspondingly to decrease the estimates of relative productivity in the computer equipment manufacturing industry. Assuming a 30 per cent share (Table 8, columns B2, C2, E2) cuts the estimated computer industry productivity substantially, to 5 per cent per year for 1978-94, for example, instead of 9 per cent. Using a 45 per cent share for semiconductors (Table 8, columns B3, C3, E3) transfers nearly all of the productivity improvement out of the computer industry, because with a 45 per cent semiconductor share, the computer industry's price decrease is almost fully accounted for by the decline in the price of its semiconductor inputs.[21] For example, the 1985-94 computer industry productivity estimate is only around 1 per cent per year.

Quite a number of caveats should be expressed about these calculations. The calculations use the computer equipment price index, even though different kinds of semiconductors go into different kinds of computer equipment. The nine types of semiconductors that are included in the semiconductor price index are more prominently associated with computers than with, say, printers, and one should relate price movements in each type of semiconductor to the price trend in the type of equipment that uses it. Nevertheless, aggregation has some advantages, particularly in view of the inadequacy of the data on the share of semiconductors in computer manufacturing.

Additionally, the price index for semiconductor memory chips and logic chips is applied to assembled boards and related devices. The semiconductor input price index may well overstate the price deadline for these computer industry inputs.

Conclusions

A comment one sometimes hears is that the BEA hedonic computer equipment price indices result in productivity change estimates for the computer industry that are (depending on the speaker) out of line with other information, not credible, too large, and so forth. There is an element of truth in these assertions. If one measures total factor productivity in the computer industry without correctly allowing for the enormous price decline in semiconductor inputs to that industry, computer productivity will be substantially overstated, because the quantity increase in semiconductor inputs is understated. The relative amount of overstatement is indicated in Table 8. It is obvious that value added in the computer industry will also be substantially overstated when semiconductor inputs are mis-measured.

When computer industry inputs are correctly measured, however, productivity in the computer industry palls beside the enormous increases in productivity in the semiconductor industry. Thus, far from being beyond the range of observation for industry productivity numbers, computer productivity increases could be described as "modest", in comparison to the productivity increases in semiconductors.

The enormous price decreases in these high-tech industries do not extend back to semiconductor manufacturing equipment. It is at first glance a bit puzzling that the performance-corrected price of semiconductor manufacturing equipment has actually risen, when we know that the technical change in this equipment makes possible the performance-corrected price drops in semiconductors, and the tremendous increases in semiconductor productivity. What story is being told here?

Technical change produces two kinds of improvements. In the first place, one can lower the cost of doing what was done before. A declining hedonic price index means that the hedonic function has shifted downward. When the computer hedonic function shifts downward, that implies that the cost of doing what one did with the computer in some previous period has decreased. Thus, one always sees that a computer with the performance capability of the typical 1972 or 1982 or 1992 computer has a lower cost today. In the case of the computer, the cost decline associated with the performance level of an earlier period turns out to be very similar to the price decline one gets from the hedonic function.

The second type of improvement wrought by technical change permits the user to do some task that was technologically impossible *at any price* at an earlier period. As noted in my 1989 paper (Triplett, 1989, pp. 199-201), enormous calculating tasks that were simply impossible in earlier periods with any computer are today routine. This gain – the extension of the product space into domains not previously inhabited by any product variety in production – cannot effectively be measured with the hedonic function alone. The hedonic function does not capture the improvement at the upper end of the product space – where one might say that the earlier period cost was infinity, or that the price index should contain the reservation price of the earlier period, which is obviously not observed in the hedonic function.

What the data in Tables 7 and 8 seem to be telling us is the following story: improvements in semiconductor manufacturing machinery are mainly of the type that makes feasible extensions of the using industry's product space into domains that did not exist earlier. Improved steppers that extend the product space of semiconductor chips wind up, the hedonic function tells us, costing more than the machines of an earlier period. Putting this another way, improvements in semiconductor manufacturing machinery do not by and large lower the cost of making an 8086 computer chip. Instead, they make possible the extension of the product space – they make it possible to produce the 286, 386, 486 and pentium chips. And indeed, this is exactly consistent with the story of technology in the computer chip industry. The lower performance chip loses its share, by and large, because its manufacturing process cannot maintain a price differential that justifies its use in most applications (Dulberger, 1989, 1993). Its relative cost saving over a more advanced chip is far lower than its lower level of performance, it loses its market share and eventually, for all practical purposes, it disappears.

This chapter is only a very preliminary and incomplete attempt to construct an integrated accounting of technological relationships. Nevertheless, it provides some insights into those relationships and presents a methodology that can be used to quantify them. It also shows how great are the errors if one tries to calculate industry productivity without correctly measuring performance-corrected inputs, as well as performance-corrected outputs of high-tech industries.

NOTES

1. In the following, I make the parallel assumption that the prices of capital services *characteristics* are proportional to capital goods *characteristics* prices. The latter assumption means that the hedonic function on capital goods prices is the same as the hedonic function on rental prices, except for a multiplicative constant.
2. See the discussion of this point for computer users and producers in Triplett (1989).
3. Strictly speaking, the relevant functions are the three cost functions that correspond to the three production functions in [3a-3c], not the production functions themselves. Deriving the cost functions presents some technical difficulties because hedonic prices for characteristics are not in general linear. Exploring this matter is not worthwhile for the purposes of this paper.
4. For the present investigation, valuable information on the technologies of semiconductors and of semiconductor manufacturing equipment was provided by VLSI Research, Inc., and by Dan Hutcheson, President of VLSI.
5. As noted in the second section of this chapter, this sentence describes the actual calculation of most of the US Bureau of Economic Analysis hedonic indices for computer equipment.
6. In Triplett (1989, pp. 159-165), I discuss alternative implementations of hedonic price indices for computer equipment.
7. An alternative, frequently encountered especially in international comparisons, is to compute the ratio of value added to (usually some subset of) inputs. One reason for doing this is the fact that value added by industry or sector is often available from national accounts. Though value added productivity has an economic interpretation, it measures something different from output-to-input productivity, and no conceptual reason for preferring value added industry productivity measures exists. Domar (1961) remarked that measuring the productivity of making shoes without leather is not very interesting; in the present context, we can paraphrase Domar by saying that we want the productivity of making computers with semiconductors, not without them.
8. As noted in note 3, some analytical difficulties exist in deriving the cost functions from the production functions, owing to the fact that the hedonic prices are not linear, as are normal goods prices. In [6], I merely assume that the functions exist (as they must), not that they are straightforward to derive. Note that because goods prices are functions of characteristics prices and characteristics quantities, the prices of the (heterogeneous) goods do not enter into the cost functions.
9. This does not necessary mean that the hedonic price index will be calculated, as have so many hedonic price indices, by inserting time dummy variables in a hedonic function. Many different methods for using information about the characteristics and about their values and prices exists. Moreover, in some cases a "matched model" price index approximates the hedonic price index.
10. The concept of the input cost index was apparently introduced into economics by Friedman (1938). A thorough (and thoroughly modern) early treatment is Court and Lewis (1942). See Diewert (1992).
11. The price index for personal computers is used in the consumption part of the US national accounts, and it and the others appear in investment, including government investment. Separate indices are computed where possible for foreign trade.
12. Slow introduction of new models and varieties has been shown as a substantial source of bias in conventional price measurement methodologies when they are applied to products with rapid technological change. As examples, see Dulberger (1993) on semiconductors and Berndt, Griliches, and Rosett (1993) on prescription drugs.
13. The seven types are given below. They were distinguished in the research because they have somewhat different characteristics, because their uses differ, and also, as noted in the text, the rate of change of prices differs across the different kinds of chips. The seven types are:
    DRAM (Dynamic random access memory)
    EEPROM (Erasable electronically programmable read-only memory)
    EPROM (Electronically programmable read-only memory)
    Flash (Flash memory; derived from EEPROMs)

ROM (Read-only memory)
Fast SRAM (Static random access memory, with access time less than 70 nanoseconds)
Slow SRAM (SRAM with access time more than 70 nanoseconds)

14. US semiconductor producers normally purchase the silicon wafers on which the integrated circuits are placed. Both wafer production and semiconductors are placed within the same US SIC industry.
15. For example, the VLSI Research, Inc. shares are actually lower in 1987 and 1992 than in most of the surrounding years.
16. I am indebted to Kenneth Flamm for helpful discussions on this matter.
17. Computers are also used in the computer industry, but are not considered in the analysis.
18. This problem is discussed by Dulberger (1993), pp. 118-120.
19. An added problem is the 1987 SIC, which was used to collect and tabulate the 1992 Census of Manufactures. Though an industry exists for Printed Circuit Boards (SIC 3672), loaded boards were omitted from the 1987 SIC. Loaded boards were therefore placed in Electronic Components, Not Elsewhere Classified (SIC 3679), along with automobile antennas, phonograph needles, and radio crystal assemblies, products that do not resemble semiconductors. Thus, US$16 billion of loaded board output is buried, without SIC documentation, in an n.e.c. category in the 1987 SIC; fortunately, it can be extracted from the input product detail information for computer purchases.
20. I applied an average of the 1977 and 1982 Census of Manufactures' shares to compute 1978-85 productivity, and an average of 1987 and 1992 shares for the 1985-94 productivity estimate.
21. The negative productivity estimates in the upper portion of column E3 should be ignored. Whatever the share of semiconductors in the 1990s, there is little evidence for a 45 per cent share in the 1970s.

REFERENCES

BERNDT, E.R. and Z. GRILICHES (1993), "Price Indices for Microcomputers: An Exploratory Study" in M.F. Foss, M. Manser and A.H. Young (eds.), *Price Measurements and Their Uses*, Studies in Income and Wealth, Vol. 57, University of Chicago Press, for the National Bureau of Economic Research, Chicago, pp. 63-93.

BERNDT, E.R., Z. GRILICHES and J.G. ROSETT (1993), "Auditing the Producer Price Index: Micro Evidence from Prescription Pharmaceutical Preparations", *Journal of Business and Economic Statistics*, No. 11, July, pp. 251-264.

CARTWRIGHT, D.W. (1986), "Improved Deflation of Purchases of Computers", *Survey of Current Business*, Vol. 66, March, pp. 7-9.

COLE, R., Y.C. CHEN, J.A. BARQUIN-STOLLEMAN, E. DULBERGER, N. HELVACIAN and J.H. HODGE (1986), "Quality-Adjusted Price Indices for Computer Processors and Selected Peripheral Equipment", *Survey of Current Business*, Vol. 66, January, pp. 41-50.

COPELAND, M.A. and E.M. MARTIN (1938), "The Correction of Wealth and Income Estimates for Price Changes", *Conference on Research in Income and Wealth*, Studies in Income and Wealth, Vol. 2, pp. 85-119 and pp. 131-35, National Bureau of Economic Research, New York.

COURT, L.M. and H.G. LEWIS (1942), "Production Cost Indices", *Review of Economic Studies*, No. 10, pp. 28-42.

DIEWERT, W.E. (1976), "Exact and Superlative Index Numbers", *Journal of Econometrics*, No. 4, May, pp. 115-145.

DIEWERT, W.E. (1992), "Fisher Ideal Output, Input and Productivity Indices Revisited", *Journal of Productivity Analysis*, No. 3, pp. 211-248.

DOMAR, E.D. (1961), "On the Measurement of Technological Change", *The Economic Journal*, No. LXXI, December, pp. 709-729.

DULBERGER, E.R. (1989), "The Application of a Hedonic Model to a Quality Adjusted Price Index for Computer Processors", in D.W. Jorgenson and R. Landau (eds.), *Technology and Capital Formation*, Massachusetts Institute of Technology Press, Cambridge, MA.

DULBERGER, E.R. (1993), "Sources of Price Decline in Computer Processors: Selected Electronic Components", in M. Foss, M. Manser and A. Young (eds.), *Price Measurements and Their Uses*, University of Chicago Press, for the National Bureau of Economic Research, Chicago, pp. 103-124.

FLAMM, K. (1993), "Measurement of DRAM Prices: Technology and Market Structure", in M. Foss, M. Manser and A. Young (eds.), *Price Measurements and Their Uses*, University of Chicago Press, for the National Bureau of Economic Research, Chicago.

FLAMM, K. (1996), *Mismanaged Trade? Strategic Policy and the Semiconductor Industry*, Brookings Institution Press, Washington, DC.

FRIEDMAN, M. (1938), "Discussion", *Conference on Research in Income and Wealth, Studies in Income and Wealth*, Vol. 2, pp. 123-130, National Bureau of Economic Research, New York.

GRIMM, B. (1995), "Quality-Adjusted Price Indices for Some Metal Oxide Semiconductor Integrated Circuits", unpublished paper, Bureau of Economic Analysis, November.

JORGENSON, D.W., F.M. GOLLOP and B.M. FRAUMENI (1987), *Productivity and U.S. Economic Growth*, Harvard University Press, Cambridge, MA.

LAU, L.J. and S. LIU (1996), "A Study of the Evaluation of the Prices of Semiconductor Manufacturing Equipment Since 1970", unpublished draft paper, Stanford University.

ROSEN, S. (1974), "Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition", *Journal of Political Economy*, No. 82, January-February, pp. 34-55.

SADÉE, N. (1996), "Computer Prices in the National Accounts: An Update from the Comprehensive Revision", US Bureau of Economic Analysis, June.

TRIPLETT, J.E. (1983), "Concepts of Quality in Input and Output Price Measures: A Resolution of the User Value-Resource Cost Debate", in M.F. Foss (ed.), *The U.S. National Income and Product Accounts: Selected Topics. Conference on Research in Income and Wealth*, Studies in Income and Wealth, Vol. 47, pp. 296-311, University of Chicago Press, for the National Bureau of Economic Research, Chicago.

TRIPLETT, J.E. (1985), "Measuring Technological Change with Characteristics-Space Techniques", *Technological Forecasting and Social Change*, No. 27, pp. 283-307.

TRIPLETT, J.E. (1987), "Hedonic Functions and Hedonic Indices", in John Eatwell, M. Milgate and P. Newman (eds.), *The New Palgrave: A Dictionary of Economics*, Vol. 2, pp. 630-634, The Macmillan Press, London.

TRIPLETT, J.E. (1989), "Price and Technological Change in a Capital Good: A Survey of Research on Computers", in D.W. Jorgenson and R. Landau (eds.), *Technology and Capital Formation*, Massachusetts Institute of Technology Press, Cambridge, MA.

TRIPLETT, J.E. and R.J. McDONALD (1977), "Assessing the Quality Error in Output Measures: The Case of Refrigerators", *Review of Income and Wealth*, No. 23, June, pp. 137-156.

US BUREAU OF ECONOMIC ANALYSIS (1996), "Improved Estimates of the National Income and Product Accounts for 1959-95: Results of the Comprehensive Revision", *Survey of Current Business*. Vol. 76, No. 1-2, January-February, pp. 1-31.

US BUREAU OF LABOR STATISTICS (1993), "Labor Composition and U.S. Productivity Growth, 1948-1990", Bulletin 2426, US Department of Labor, Washington, DC, December.

WYCKOFF, A.W. (1995), "The Impact of Computer Prices on International Comparisons of Labour Productivity", *Economics of Innovation and New Technology*, No. 3, pp. 277-293.