NBER WORKING PAPER SERIES

PRODUCT INNOVATIONS, PRICE INDICES AND THE (MIS)MEASUREMENT OF ECONOMIC PERFORMANCE

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Working Paper No. 3261

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
February 1990

This paper was presented at the OECD conference on Science, Technology and Economic Growth, Paris, June 1989, and at the workshop on Productivity at the NBER Summer Institute. I am grateful to participants in both conferences for helpful comments. This paper is part of NBER's research program in Productivity. Any opinions expressed are those of the author not those of the National Bureau of Economic Research.

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ABSTRACT

The goal of this paper is to address the problem of 'product innovations' (i.e. new goods, increased variety, and quality change) in the construction of price indices and, by extension, in the measurement of economic performance. The premise is that a great deal of technical progress takes the form of product innovations, but conventional economic statistics fail by and large to reflect them. The approach suggested here consists of two stages: first, the benefits from innovations are estimated with the aid of discrete choice models, and second, those benefits are used to construct 'quality adjusted' price indices. Following a discussion of the merits of such approach vis a vis hedonic price indices, I apply it to the case of CT (Computed Tomography) Scanners. The main finding is that the rate of decline in the real price of CT scanners was a staggering 55% per year (on average) over the first decade of the technology. By contrast, an hedonic-based index captures just a small fraction of the decline, and a simple (unadjusted) price index shows a substantial price increase over the same period. Thus, conventional economic indicators might be missing indeed a great deal of the welfare consequences of technical advance, particularly during the initial stages of the product cycle of new products.

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1. Introduction

The purpose of this paper is to address the problem of 'product innovations' in the construction of price indices and, by extension, in the measurement of economic performance. A great deal of technical progress takes in fact the form of new goods, improved qualities and increased variety, but conventional economic statistics fail to reflect them, quite likely by a long shot. Indeed, conventional index-numbers methods are ill equipped to capture quality change, and though hedonic price indices may offer some paliative, they constitute by no means a full cure. As it stands now, then, there is no proven way of incorporating product innovations into measures of economic performance, and hence no way of assessing the possible discrepancies that might exist on that account between 'real' and conventionally measured aggregate product and growth.

The method suggested here for the construction of quality-adjusted price indices consists of two stages: first, the econometric estimation of the welfare gains from product innovation, and second, the design and computation of real price indices that build upon those gains. The first stage draws from discrete choice models and from the 'characteristics approach' to demand theory, leading to estimates of the preferences for the attributes of products, and from there to value measures of quality change. Following a brief review of this approach in section 2 (a full exposition is in Trajtenberg, 1989), I take up in section 3 the main task of the paper, namely, how to express the gains from innovation as changes in 'real' prices. Two alternative indices are developed, one suited for incremental advances only, the other capable of capturing the impact of drastic innovations as well. The central idea behind the second index is to use the estimated gains in order to infer the consumers' reservation price for the innovation, and then compute the index on the basis of the difference between the actual and the shadow prices. Section 4 discusses the merits of the proposed method vis a vis the use of hedonic price indices, a contrast that is made vivid in section 5 where I apply the two methods to the case of a specific innovation, CT (Computed Tomography) Scanners. The main finding is that the rate of decline in the quality-adjusted price of CT scanners was a staggering 55% per year (on average) over the first decade following the introduction of the innovation. By contrast, an hedonic-based index captures just a small fraction of the decline, not to speak of the unadjusted price index, which shows a substantial price **increase** over the same period.

Thus, conventional indices might be missing indeed a great deal of the welfare consequences of technical advance, particularly during the initial phases of the life cycle of new products.[1] In light of the evidence suggesting that technical change has been increasingly taking the form of product rather than process innovation (see e.g. Scherer, 1984), the gap between 'real' and official indicators of aggregate economic performance might be widening over time. This in turn may have serious implications for the design of policies aimed at manipulating the phenomena that those indicators purportedly represent. As discussed in the concluding section, though, it is not yet clear whether the proposed approach could be applied on a wide scale to the

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[1]This is above and beyond the problem of long delays in incorporating new goods in the computations of say, the CPI. That is, even if new goods were incorporated right away in existing price indices, the problem of mismeasurement by and large would remain.

construction of price indices, primarily because of its voracious data requirements. Nevertheless, we should be well aware of what we are missing, and develop the tools to eventually correct that.

2. Assessing the Value of Product Innovations

In view of the fact that the 'output' of innovative activities does not present itself in countable units of any sort, innovations can be quantified only in value terms, that is, in terms of the incremental social surplus that they generate. That is relatively easy to do (in principle) in the case of process innovations, since those involve the displacement of cost functions along a fixed demand schedule (see for example Griliches, 1958). On the other hand, if innovations take the form of the introduction of new products or changes in the quality of existing ones, then their value to consumers cannot be represented simply as a cost saving, but requires instead a more elaborate framework.

The approach suggested in Trajtenberg (1989), (1990) draws primarily from the 'characteristics approach' to demand theory (see e.g. Lancaster, 1979) and from the econometrics of discrete choice.[2] The basic idea is as follows: consider a technologically dynamic product class as it evolves over time, and assume that the different brands in it can be described well in terms of a small number of attributes and price. Product innovation can then be thought of in terms of changes over time in the set of available products, both in the sense that new brands appear, and that there are improvements in the qualities

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[2] Here I just sketch the essence of the approach; for a full discussion see Trajtenberg (1990), Ch. 1.

of existing products. Applying discrete choice models to data on the distribution of sales per brand, and on their attributes and prices, one can estimate the parameters of the demand functions and, under some restrictions, of the underlying utility function. The social value of the innovations occuring between two periods can then be calculated as the benefits of having the latest choice set rather than the previous one, in terms of the ensuing increments in consumer and producer surplus. That is, given an estimated 'social surplus' function W(.) and the sets of products S_t and S_{t-1} offered in two successive periods, the value of innovation would be measured by[3]

$$\Delta W_t = W(S_t) - W(S_{t-1}). \tag{1}$$

The main problem, then, is to find a suitable specification for the function $W(S_t)$, and be able to retrieve its parameters from observable data. Assuming discreteness, both in the sense that the choice sets S_t's are discrete and that consumers purchase a single unit of a single product, one can resort for that purpose to discrete choice models, and make use of the associated welfare analysis (see McFadden, 1981). In particular, I rely on the multinomial logit model, which renders the well-known choice probabilities,[4]

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[3]As said above, W(S) is meant to comprise both consumer and producer surplus. However, since profit is a well-defined magnitude whose measurement does not pose special conceptual problems in the present context, ΔW will be associated with gains from innovations in terms of consumer surplus only.

[4]For simplicity, I shall ignore throughout the vector of personal attributes (of the individual buyer) that would normally appear as an argument in $V(\cdot)$; for the time being I ommit also the time index, but that will appear in subsequent sections.

$$(2) \qquad \pi_j = \exp V(z_j, p_j) \;/\; \sum_i^n \exp [V(z_i, p_i)]. \qquad j=1,\dots,n$$

where z is the vector of attributes, p price, n the number of alternatives in the choice set, and $V(\cdot)$ the branch of (the deterministic component of) the indirect utility function related to the product class in question. Ignoring income effects, and assuming that the utility function is additive-separable leads to

$$(3) \qquad V_i = \alpha(y - p_i) + \phi(z_i)$$

where α stands for the (constant) marginal utility of income. Integrating the probabilistic demand functions in (2) with the V_i's specified as in (3) one obtains measures of consumer surplus of the form,

$$(4) \qquad W(S) = \ell n \, [\sum_{i=1}^{n} \exp(-\alpha p_i + \phi(z_i)] \;/\; \alpha$$

This surplus function is then the key element in assessing the value of product innovations: after estimating the choice probabilities in (2), one can retrieve the parameters of (4), and compute the benefits from innovations occuring between any two adjacent years, as in (1).

3. The Construction of Quality-Adjusted Price Indices on the Basis of ΔW

Suppose then that we have estimated the multinomial logit model as in (2) and computed the yearly gains ΔW_t from (4) and (1); the question now is how to construct on the basis of those ΔW's a 'real' price index that would faithfully reflect the value of innovations thus measured. The procedure suggested here involves relying on the expenditure function dual to (4), and using it to compute the hypothetical price change that would have resulted in the same welfare effect (measured by ΔW) as the innovations that actually took place. In that sense the proposed index belongs to the class of 'cost-of-living' - or Konüs - indices (see Diewert, 1987). Consider the function,

$$\Upsilon = \frac{y}{\bar{P}} + W(S) = \frac{y}{\bar{P}} + \ell n\, [\sum_{i=1}^{n} \exp(-\alpha p_i + \phi(z_i)]/\alpha$$

where $\bar{P}$ is the price index for all goods other than those in S (i.e. the price of the numeraire, implicitly assumed before to be unity), and the prices p_i appearing in W(S) are now 'real', i.e. $p_i = \tilde{p}_i/\bar{P}$, where $\tilde{p}_i$ are nominal. Note that Υ is homogenous of degree zero in prices and income, and convex in prices. Thus, and as shown in McFadden (1981), Υ above is in fact an indirect utility function, and is therefore invertible to a (concave) expenditure function, $e(S, \Upsilon^o) = \bar{P}\cdot[\Upsilon^o - W(S)]$. Given that $\bar{P}$ will not play a role in the forthcoming analysis, we can ignore it and write,

(5) $$e(\Upsilon^o, p, Z) = \Upsilon^o - \ell n\, [\sum_{i=1}^{n} \exp(V_i)\,]/\alpha$$

where p stands for the vector of prices of all brands in S, and Z for the matrix of their attributes. Assume now that innovations occur from period t-1 to t, taking the form of improvements in the attributes of - some of - the products in the choice set (their prices may change as well). Using (1), (4) and (5), the welfare gains from those innovations would be measured by $\Delta W_t = \ell n\,[\Sigma \exp(V_{it})\,]/\alpha - \ell n\,[\,\Sigma \exp(V_{it-1})\,]/\alpha$, leading to

$$\text{(6)} \qquad \Delta W_t = e(\gamma^{\circ}, p_{t-1}, Z_{t-1}) - e(\gamma^{\circ}, p_t, Z_t)$$

Thus, ΔW as expressed in (6) measures the analog in the present context of a compensating variation, i.e. it answers the question "how much income could be taken away from the consumer so as to leave him indifferent between facing the old choice set, and the new (improved) one but with the lesser income?" However, since $e(\cdot)$ is linear additive in γ (recall that income effects were assumed away), then the reference utility level (or the income level in the dual) does not matter, and hence the compensating and equivalent variations are one and the same. Thus, we can ommit γ° from (6) and write:

$$\text{(6)'} \qquad \Delta W_t = e(p_{t-1}, Z_{t-1}) - e(p_t, Z_t)$$

After obtaining estimates of ΔW_t using the method outlined in section 2, one can construct two different price indices that would reflect the quality changes embedded in S_t vis a vis S_{t-1}. The first requires that we solve for δ_t out of,

$$\text{(7)} \qquad \Delta W_t = e[p_{t-1}, Z_{t-1}] - e[\,(1-\delta_t)\cdot p_{t-1}, Z_{t-1}]$$

(to insist, ΔW_t in (7) is a known magnitude, and so are the parameters of the expenditure function). That is, δ_t is the hypothetical average price reduction that would have had the same welfare consequences as the innovations that actually took place. In other words, consumers would had been equally well off if they had been offered the **old** set of products at prices lower by a factor of δ_t, as they actually are by virtue of having the **new** set that incorporates the better qualities (i.e. they would be indifferent between $[(1-\delta_t)\cdot p_{t-1}, Z_{t-1}]$ and $[p_t, Z_t]$). From a computational viewpoint, the values of δ_t can be obtained from (7) with methods of iterative search.[5] However, if one is willing to use a somewhat more restrictive notion of 'average price change', then δ_t can be computed in a much simpler way. This is done as follows: the price of each brand at time t can always be written as $p_{it} = \bar{p}_t + \Delta p_{it}$, where $\bar{p}_t$ is the average across brands. Now, suppose that the changes in prices from period t-1 to t take the from,

$$p_{it} = (1 - \delta_t)\ \bar{p}_{t-1} + \Delta p_{it-1}$$

that is, the distribution of prices moves leftwards by a factor of $(1 - \delta_t)$, but the variance remains the same. It is easy to show that in such a case (7) simplifies to,[6]

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[5]Note from (6)' and (7) that this is the same as solving for δ_t out of $e[(1-\delta_t)\cdot p_{t-1}, Z_{t-1}] = e[p_t, Z_t]$.

[6]Recall that $W = \ell n[\Sigma_i \exp(\phi_{it} - \alpha p_{it})]/\alpha$, where $\phi_{it} = \phi(z_{it})$. Given $p_{it} = \bar{p}_t + \Delta p_{it}$, $W = \ell n[\Sigma_i \exp(\phi_{it} - \alpha\bar{p}_t - \alpha\Delta p_{it})]/\alpha = \ell n\{[\Sigma_i \exp(\phi_{it} - \alpha\Delta p_{it})]$

$$\Delta W_t = \delta_t \bar{p}_{t-1} \tag{8}$$

and hence δ_t obtains immediately as the ratio $\Delta W_t/\bar{p}_{t-1}$. To reiterate its meaning, this ratio stands for the percentage average price reduction that would be equivalent, from a welfare viewpoint, to the innovations valued ΔW_t. This is a very convenient result for computational purposes, and it may help clarify the meaning of the measure ΔW_t itself (e.g. it may be easier to visualize ΔW_t as a displacement along the price dimension). Having arrived at the series $\{\delta_t\}$, a quality adjusted price index can then be computed simply as $I^1_t / I^1_{t-1} = (1 - \delta_t)$, with $I^1_0 = 100$ (the superscript is meant to distinguish between the two alternative indices)

The second price index obtains by solving for φ_t from,[7]

$$\Delta W_t = e[\ (1+\varphi_t)\cdot p_t,\ Z_t] - e[\ p_t,\ Z_t] \tag{9}$$

That is, if prices of the improved products had been $(1+\varphi_t)$ times higher than actual prices, then the implied percentage price reduction of $\delta'_t = \varphi_t/(1+\varphi_t)$ would be equivalent - from the point of view of its welfare effects - to the quality improvements that took place. Thus, $(1+\varphi_t)\cdot p_t$ can

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$\exp(-\alpha\bar{p}_t)\}/\alpha = -\bar{p}_t + \ell n[\Sigma_i \exp(\phi_{it} - \alpha\Delta p_{it})]/\alpha$. Therefore, given $\bar{p}_t = (1-\delta_t)\bar{p}_{t-1}$. (7) reduces to $\Delta W_t = \bar{p}_{t-1} - (1 - \delta_t)\bar{p}_{t-1} = \delta_t\bar{p}_{t-1}$.

[7] This is similar in spirit to a suggestion by Hicks (1940) on how to treat the introduction of new goods; Diewert (1980) shows an econometric procedure to actually implement the suggestion (which Hicks himself thought would not be possible).

be interpreted as the reservation price for the innovations embedded in S_t: if the products in that set were offered at an average price of $(1+\varphi_t)\cdot\bar{p}_t + \epsilon$ (for any small $\epsilon > 0$), the consumer would prefer to have the older set instead. Assuming again that the price change consists just of a displacement in the mean price, φ_t would obtain simply from,

$$(10) \qquad (1+\varphi_t) = (\Delta W_t + \bar{p}_t) \,/\, \bar{p}_t \;\Rightarrow\; \varphi_t = \Delta W_t \,/\, \bar{p}_t \,,$$

implying a percentage price reduction of,

$$(11) \qquad \delta'_t \equiv \varphi_t / (1+\varphi_t) = \Delta W_t \,/(\Delta W_t + \bar{p}_t)$$

The associated price index would be $I^2_t \,/\, I^2_{t-1} = 1/(1+\varphi_t) = (1 - \delta'_t)$.

Comparing the two indices, it can be shown that $\delta'_t \leq \delta_t$, i.e. the first index will always show a larger 'quality-ajusted' price reduction. This is easily seen in the case where $\bar{p}_t = \bar{p}_{t-1} = \bar{p}$:

$$\delta_t = \frac{\Delta W_t}{\bar{p}} > \frac{\Delta W_t}{\Delta W_t + \bar{p}} = \delta'_t$$

That is, ΔW_t (to be interpreted here as a notional average price discount equivalent to the quality improvements), would certainly represent a higher percentage of the base price $\bar{p}$, than of the - necessarily higher - 'reservation price' $(\Delta W_t + \bar{p})$.[8] In general, though, $\bar{p}_t \neq \bar{p}_{t-1}$, but the above

[8] This is the same sort of discrepancy as the one that may arise when computing the elasticity of say, a demand function, along a segment (i.e. for

inequality will still hold. Denoting $\bar{p}_t = (1+\lambda_t)\cdot\bar{p}_{t-1}$, it is easy to show that $\delta' = \frac{\delta_t}{1+\lambda_t+\delta_t}$, and hence that $\delta'_t < \delta_t$;[9] notice also that the difference between the two indices grows with λ_t.

Clearly, the two indices are equally legitimate and have equally well defined welfare interpretations. There is, however, a technical difference between them that makes the second index the only feasible one when innovations are 'drastic' i.e. when the ΔW's are very large (relative to prices). Note that there is no reason whatsoever for ΔW_t to be smaller than $\bar{p}_{t-1}$ (i.e. there is no reason for the value of innovations to be bounded by the average price of the products embedding those innovations), and hence it may happen that $\Delta W_t > \bar{p}_{t-1}$ (i.e. that $\delta_t > 1$). That would mean simply that, even if the products that existed in period t-1 were to be sold at zero price, consumers would still prefer to have instead the more advanced products and pay their full price. In other words, in order for consumers to be indifferent between facing the period t choice set and that of period t-1, they would have to be offered the t-1 products for free, plus a 'bribe' (or 'negative price') of $(\Delta W_t - \bar{p}_{t-1})$ dollars. However, since negative prices are not allowed one could not use in such a case I^1_t, since $\delta_t > 1$ would imply a negative value for the index. On the other hand, if ΔW_t is larger

a discrete price change), rather than at a point.

[9]This is so provided that, if $\lambda_t < 0$ (i.e. if there is an average price reduction), then $|\lambda_t| \leq \delta_t$. But that is always the case (unless there is a quality deterioration): if the qualities of products don't change from t-1 to t but $\bar{p}_t = (1-\lambda)\bar{p}_{t-1}$, then $\Delta W_t = \lambda\bar{p}_{t-1}$, and hence $\delta_t = \lambda_t$. If at the same time qualities improve, then $\delta_t > \lambda_t$.

than $\bar{p}_t$ and hence $\varphi_t > 1$, the second index is still well defined: the hypothetical reservation prices that would make the consumer indifferent between the improved (but more expensive) products and the older set can be as high as necessary.

Thus, if innovations in a given field are at times very substantial there is no choice but to use the second index only. On the other hand, if a field consistently displays just incremental innovations it may be worth considering some sort of average between the two indices, and/or using the average of the mean price in the two periods to compute either index. Finally, it is worth noting that those indices can accomodate well cases of 'negative' innovations, resulting in negative values of ΔW_t. That would be the case, for example, if there is no change in the qualities of products, but prices rise by λ%: it is easy to see that in such a case $\delta'_t = \delta_t = -\lambda$, i.e. both indices would faithfully and equally reflect the price hike.

4. ΔW-based Indices versus Hedonic Prices

Having put forward price indices based on the measures ΔW, it is important to step back and ask whether one really needs the elaborate method outlined above in order to obtain reasonably good deflators for rapidly changing goods: could it not be that indices based on hedonic price regressions would do the job just as well?[10] Note that this question is

[10] The hedonic method is certainly much simpler, its data requirements are more modest, it is well known and commands wide acceptance. Moreover, since the early sixties various government agencies have been considering using it in the construction of price indices, and in fact the BEA recently started to compute an hedonic index for computers, in collaboration with IBM. Thus, if both methods were roughly equivalent, surely one would not hesitate in siding with the hedonic approach.

essentially the same as asking whether or not there is a meaningful distinction between process and product innovations: the use of hedonic price indices (in lieu of ΔW-based indices) is justified only when 'quality' is merely a redefinition of quantity, and hence 'product innovation' is just process innovation in disguise.

4.1 *Quality-Adjusted Price Indices in The 'Repackaging' Case*

The answer to the question just posed can essentially be found in Fisher and Shell (1972) classic work on the theory of price indices (even though the question there was not quite put in those terms): hedonic-based price indices (or a price/performance ratio if quality is unidimensional) would suffice to account for quality change only in the 'repackaging' case.[11] If the choice set consists of one good only (say, good 1), and 'quality' can be fully accounted for with one parameter θ, 'repackaging' implies that the corresponding argument in the utility function is just θx_1. That is, θ is sort of the amount of services provided by the good, and hence 'quality change' (meaning $\theta_t > \theta_{t-1}$) amounts essentially to a redefinition of units. In such a case one can define a 'price-performance' ratio p_1/θ such that, for any θ,

$$(12) \qquad e(\gamma^o, p_1, p_2, \ldots, p_n; \theta) = e(\gamma^o, p_1/\theta, p_2, \ldots, p_n)$$

and the implied 'quality adjusted' price index would simply be (p_{1t}/θ_t) / (p_{1t-1}/θ_{t-1}). Thus, if θ were easily observable (as when it is indeed just a

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[11]See also Usher (1980); Diewert (1980) resorts to repackaging as well in providing a justification for the use of the hedonic approach to deal with the new goods problem.

matter of redefining units), accounting for 'quality change' would be a very simple matter. Notice, importantly, that in such a case the distinction between process and product innovations all but vanishes (as does the quality-quantity dichotomy): defining the relevant price as p_1/θ, rather than just p_1, it is clear that technical change that brings about a reduction in costs leading in turn to a decrease in the unadjusted price p_1 (i.e. a process innovation) is exactly equivalent to a 'product' innovation that results in the proportional enhancement of θ.

When the choice set consists of $n > 1$ brands, 'repackaging' implies that the corresponding branch of the utility function takes the form $U(\Sigma_i^n \theta_i x_i)$. Clearly, if $U(\cdot)$ is common to all consumers, then in order for more than one brand to be purchased in a cross-section it must be that $p_i/p_j = \theta_i/\theta_j$. Denoting by $\tilde{p}_o$ the quality-adjusted price of the reference variety, one can always write $p_i = \tilde{p}_o \theta_i$. Furthermore, if θ_i is not one-dimensional but depends upon a vector of attributes $\bar{z}_i$, then (see for example Deaton and Muellbauer, 1980),

$$\log p_i = \log \tilde{p}_o + \log \theta(\bar{z}_i) \tag{13}$$

which is one of the forms that estimated hedonic price functions commonly take. In a two-year panel, for example, the term $\log \tilde{p}_o$ would obtain as the coefficient of a time dummy variable, and can be taken as a sufficient price index in the sense of (12) above (i.e. $\tilde{p}_t$ would be the equivalent in this context of the price-performance ratio p_t/θ_t).[12] To insist, the point is that

[12] Even this simple case is subject to several qualifications. In

the hedonic price function by itself just allows to account for more than one attribute in computing price indices, but such indices can serve as sufficient indicators of 'quality' change only in the highly restrictive context of the repackaging case.[13]

4.2 *The Performance of Hedonic Price Indices: a Preliminary Assessment*

Pure repackaging being a rarity, it would seem then that hedonic price indices should be discarded outright; but, how damning are departures from repackaging likely to be for the accuracy of those indices? Considering their appeal otherwise (recall footnote 11), this question certainly deserves further scrutinity. That is taken up empirically in next section, where both ΔW-based and hedonic indices are computed and compared for the case of CT scanners. However, in order to have a better sense for what those comparisons may entail, it is worth examining in a heuristic manner how hedonic price indices are likely to perform in various stylized situations.

As already suggested, if a price index is to account faithfully for quality change it should measure the 'distance' (in money metric) between the attainable utility level before and after the innovation. Consider the case whereby innovations occur so that there is a downward shift in the hedonic function, as shown in Figure 1.a. In the simplest possible situation (abstracting from discreteness, aggregation problems, and income effects), the

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particular, if the budget constraint in attributes space is non-linear (as it is most likely to be), then the estimation of (13) involves what can be construed as errors of aggregation.

[13]See Trajtenberg (1990), ch.1, for an extensive discussion of how the notions of repackaging and of quality relate to the nature of the attributes of products.

distance between the indifference curves labeled W^o and W' would be a good approximation to the monetized welfare gains associated with the innovations that induced the displacement in the hedonic function. Thus, the coefficient of a time dummy in a hedonic regression pooling adjacent years will accurately measure those gains, and the resulting quality-adjusted price index could thus be taken as a faithful indicator of the changes occured.

In order to illustrate this equivalence, assume that there is only one attribute, z, and that innovation consists of augmenting the quantity of that attribute in all brands by the same absolute magnitude, Δz (if prices remain unchange, as it is assumed, that will result in a parallel displacement of p(z) as in Figure 1.a). Evaluating this change with the measure ΔW of equation (6), and further assuming that $V(\cdot)$ is linear in z,

$$\Delta W = \ell n \; \{ \; \Sigma \; \exp[-\alpha p_i + \beta \; (z_i + \Delta z)]\}/\alpha \; - \; \ell n \; [\; \Sigma \; \exp(-\alpha p_i + \beta \; z_i)]/\alpha = \boldsymbol{\beta \; \Delta z/\alpha}$$

Now, if the hedonic function is also linear, i.e. $p_i = \bar{p} + \gamma z_i$, then it is easy to see that the implied price index will change by $\Delta\bar{p} = \gamma \Delta z$.[14] Thus, $\Delta\bar{p}$ and ΔW will be proportional to each other and, under a suitable normalization, they will be identical. This is of course a highly simplified case, but the gist of the argument applies in more complex situations as well.

By contrast, consider now Figure 1.b: innovation in this case consists of

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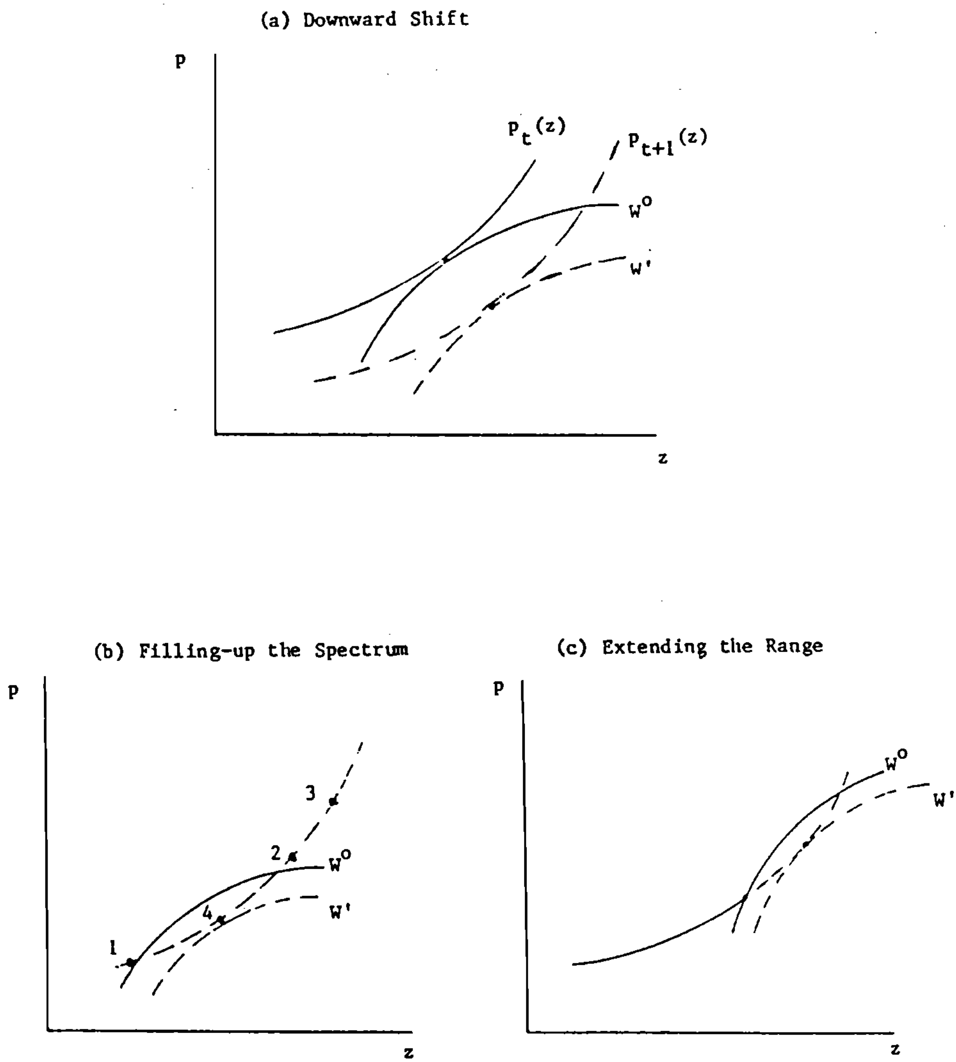
[14]Similarly, if z enters both in the utility function and in the hedonic equation as log z, then a **proportional** change in the z of all brands (i.e. $z_{t+1} = \lambda z_t$, $\lambda > 1$, for all i) will render the same result.

Figure 1

Alternative Effects of Innovation on Hedonic Price Functions



the filling-up of the spectrum of products, e.g. in the base period only brands 1, 2 and 3 exist, but in the second period products such as 4 and 5 are added to the choice set. As the figure suggests, in this case there will be no change whatsoever in the hedonic price function, and hence a price index based on it will altogether fail to register the occurance of the innovations. On the other hand, a measure such as ΔW will certainly be positive, and could in fact be quite large. Figure 1.c illustrates a similar situation, except that innovation takes there the form of extending the range of available products, i.e. higher quality brands are introduced, priced (approximately) in accordance to the base hedonic function. Again, this type of innovations will leave no trace in the hedonic price index, whereas the actual gains may be substantial. Moreover, in the last two types of cases ΔW may be positive and at the same time the hedonic-adjusted price index might actually increase, suggesting the occurance of negative innovations (for an empirical finding of that nature, see Alexander and Mitchel, 1985).

Clearly, the three stylized types of changes described are equally legitimate as instances of product innovations, and a priori it would appear that they are equally likely. However, there is some evidence to the effect that the latter two types are much more prevalent during the initial stages of the 'product cycle', when brands proliferate up and down the spectrum, spanning new market segments. On the other hand, downward shifts in the hedonic function tend to occur later on, in the wake of widespread imitation and price competition. If so, adjusting for quality changes with the aid of hedonic price functions may be a reasonable first approximation for well-established sectors, but not for tracing the emergence of new ones. As shown in Trajtenberg (1989), the bulk of the gains from innovation in the case of CT scanners occured very early-on in the development of the field. If those results are typical (and there is some room to believe so), then the picture painted by hedonic-based price indices may systematically understate a great deal of the 'action' occuring in the technologically progressive sectors of the economy.

5. AW-Based versus Conventional Indices in the Case of CT Scanners

Having measured the welfare gains from innovation using the approach of section 2 in one particular case, namely CT Scanners, it is now possible to assess how far off-the-mark other indices would have been in this case, and thus get a sense for the extent to which prevalent economic indicators might be presenting a distorted image of the dynamic performance of high tech sectors.

First, a few words about the innovation: Computed Tomography (CT) is a highly sophisticated diagnostic technology that produces cross-sectional images of the interior of the body, allowing to visualize with high accuracy vital organs that could not at all be seen before (such as the brain). It has been hailed as one of the most remarkable medical innovations of recent times, comparable to the invention of radiography. Originally developed at the British firm EMI in the early seventies, CT soon attracted some twenty other firms worldwide, and the fierce competition that ensued brought about a breathtaking pace of technical advance. The diffusion of the new systems proceeded very fast as well: first introduced in the US in 1973, by 1985 almost 60% of hospitals (with more than 100 beds) had at least one system installed. The pace of innovation in CT subsided in the mid-eighties as the technology matured and ceded its dominant place to new technological developments, particulary to Magnetic Resonance Imaging. Two types of scanners were developed: head only, and whole-body systems (the latter appeared later, but they have dominated the scene ever since the mid-seventies). The price and technological evolution of the two types of scanners has been very different: head scanners become simpler and cheaper over time (particulary since 1978), whereas body scanners exhibited a tremendous pace of technical advance and a corresponding steep rise in prices. Thus, I report separate figures for each type, as well as for all CT scanners.

Table 1 shows the estimates of ΔW_t and the mean prices (those figures are taken from Trajtenberg, 1989): notice that ΔW_t exceeds $\bar{p}_t$ during the first 4 years following the introduction of CT, and hence one can compute only the second index $\delta'_t \equiv \varphi_t/(1+\varphi_t) = \Delta W_t/(\Delta W_t + \bar{p}_t)$.[15] That is, there were drastic technical advances in CT during the initial period (as reflected in the large values of ΔW_t), and hence the first index, requiring that $\Delta W_t < \bar{p}_{t-1}$, is not applicable in the present case. Notice that the index δ' indicates the occurance of 'negative innovations' (i.e. increases in 'real' prices) in head scanners in 1979, 1980 and 1982, in spite of a downward trend in nominal prices. This had to do with the shrinking of the set of head scanners offered in the market, as body scanners gained dominance.

The computation of hedonic indices can be done in various ways, of which the following were considered here: (a) weighted versus unweighted regressions

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[15] Notice that $\delta' > 0$ signifies a real price reduction, but in order to avoid confusion the figures for this index reported in the tables correspond to $-\delta'$, i.e. minus x% means indeed a price reduction of x%.

Table 1

Computation of the ΔW-based Price Indices for CT Scanners

Year	Head Scanners ΔW	$\bar{p}$	δ'	Body Scanners ΔW	$\bar{p}$	δ'	All Scanners ΔW	$\bar{p}$	δ'
1974							4,391	370	-0.92
1975							875	372	-0.70
1976	994[a]	374	-0.73	1967[a]	471	-0.81	2,961	448	-0.87
1977	37	354	-0.09	724	573	-0.56	620	541	-0.53
1978	257	167	-0.61	15	620	-0.02	82	494	-0.14
1979	-10	154	+0.07	158	667	-0.19	108	515	-0.17
1980	-16	154	+0.12	83	739	-0.10	64	626	-0.09
1981	7	150	-0.04	190	827	-0.19	174	770	-0.18
1982	-3	150	+0.02	209	850	-0.19	195	804	-0.19

[a]Imputed figures.

ΔW: Social gains from innovation in CT Scanners, computed according to equations (4) and (1), in current prices.

$\bar{p}$: Weighted mean price (weights: annual unit sales).

δ': ΔW-based price change: $\delta'_t = -\Delta W_t/(\Delta W_t + \bar{p}_t)$.

Source of data on ΔW and $\bar{p}$: Trajtenberg (1989).

(the weights being annual unit sales of each brand); (b) pooled regressions with dummy variables for each year, versus separate regressions for each pair of adjacent years (see Griliches 1971 for a discussion of the relative merits of each method). Table 2 presents the estimated hedonic equations pooling all years, weighted and unweighted, and the corresponding hedonic indices are computed in tables 3 and 4 (the regressions for adjacent years are not reported since there were too many of them). The functional form in all cases is the double-log, and hence the coefficients of the yearly dummies, properly adjusted, can be taken as the 'pure' (or 'quality adjusted) price change, in percentage terms.[16]

The results of all four hedonic specifications considered are quite similar when contrasted with the ΔW-based index: the 'real' price reductions that occured in CT were much larger than what the hedonic method is able to uncover, particulary during the first few years. Table 5 shows that in a condensed way: if no correction is made at all, one would conclude that CT scanners were about 2.5 times more expensive in 1982 than a decade earlier, and hence that we are significantly worse off on that account. Using the hedonic technique significantly alters this assesment: the quality-adjusted hedonic index goes down from 100 to 27, implying an average annual price decrease of 13%. Still, that is a far cry from the actual pace of technical

[16] Denote the coefficient of the dummy for year t in a pooled hedonic regression as β_t : the percentange 'pure' price change between year t-1 and t is computed as $\exp(\beta_t - \beta_{t-1})$. Recall that for small β's, $\exp \beta \cong \beta$, hence the common practice of taking just the differences $\beta_t - \beta_{t-1}$. In the present case, though, those differences are often quite large, and hence one should take indeed the exponent.

Table 2
Hedonic Price Regressions

	All Scanners		Body Scanners		Head Scanners	
	W	UnW	W	UnW	W	UnW
constant	8.12	7.99	6.73	6.9	6.25	6.78
	(28.1)	(27.7)	(21.1)	(53.2)	(10.4)	(9.8)
Head Dummy	-.22	-0.26				
	(-3.1)	(-3.7)				
Speed	-0.22	-0.19	-0.14	-0.15	-0.04	-0.10
	(-9.0)	(-8.6)	(-13)	(-8.8)	(-0.7)	(-1.7)
Resolution	-0.53	-0.44	-0.30	-0.44	0.35	0.11
	(-5.4)	(-4.7)	(-7.7)	(-7.4)	(0.9)	(0.30)
Recon.Time	-0.05	-0.06	-0.03	-0.05	-0.12	-0.10
	(-2.2)	(-3.5)	(-3.5)	(-3.7)	(-2.3)	(-2.5)
D74	0.07	-0.43			0.15	0.09
	(0.3)	(-1.5)			(0.7)	(0.2)
D75	-0.49	-0.54	0.06	0.04	0.15	-0.24
	(-2.0)	(-2.0)	(0.2)	(0.3)	(0.5)	(-0.6)
D76	-0.78	-0.67	0.13	0.13	0.06	-0.16
	(-3.2)	(-2.6)	(0.42)	(1.1)	(0.2)	(-0.4)
D77	-0.95	-0.84	0.11	0.03	-0.005	-0.28
	(-3.9)	(-3.2)	(0.34)	(0.3)	(-0.0)	(-0.7)
D78	-1.19	-0.96	0.10	-0.01	-0.73	-0.52
	(-4.7)	(-3.6)	(0.30)	(-0.1)	(-2.1)	(-1.2)
D79	-1.28	-1.05	0.07	-0.03	-0.82	-0.88
	(-5.0)	(-3.9)	(0.21)	(-0.2)	(-2.3)	(-1.9)
D80	-1.26	-1.12	0.10	-0.08	-0.79	-1.01
	(-4.8)	(-4.1)	(0.31)	(-0.7)	(-2.2)	(-2.2)
D81	-1.20	-1.06	0.18	0.02	-0.83	-1.03
	(-4.4)	(-3.9)	(0.56)	(0.16)	(-2.2)	(-2.2)
D82	-1.30	-1.11	0.09	-0.04		-0.98
	(-2.2)	(-4.0)	(0.24)	(-0.3)		(-2.1)
Obs.	115	136	81	96	33	39
R^2	0.84	0.81	0.94	0.83	0.89	0.69

t-values in parenthesis (see notes on next page)

Notes to Table 2

In the headings: W means weighted regressions (annual unit sales as weights), and UnW stands for unweighted regressions.

The three attributes (speed, resolution and reconstruction time) are measured so that 'less is better' (e.g. speed is measured in seconds per scan, and hence the faster a scanner is, the better). Thus, we expect that their coefficients in the hedonic regressions will be negative. All three are in logs. 'Head' is a dummy variable for head scanners.

There are less observations in the weighted regressions, since some of the CT scanners had zero sales.

Table 3

'Quality-Adjusted' Price Changes: Hedonic versus AW-based Indices
All Scanners

Year	Hedonic: Pooled Unweighted	Hedonic: Pooled Weighted	Hedonic: Adjacent Unweighted	Hedonic: Adjacent Weighted	δ'_t
1974	-0.43	+0.07			-0.92
1975	-0.11	-0.34*	+0.03	+0.01	-0.70
1976	-0.12	-0.25*	+0.13	+0.03	-0.87
1977	-0.16	-0.16*	-0.05	+0.01	-0.53
1978	-0.11	-0.21*	-0.09	-0.17*	-0.14
1979	-0.09	-0.09	-0.08	-0.04	-0.17
1980	-0.07	+0.02	-0.08	+0.02	-0.09
1981	+0.06	+0.06	+0.06	+0.05	-0.18
1982	-0.05	-0.10	-0.08	-0.14	-0.19

*: Differences (with previous year) statistically significant ($\alpha = 0.05$ or better).

Table 4

'Quality-Adjusted' Price Changes: Hedonic versus AW-based Indices
Separate Figures for Head and Body Scanners

4.a Head Scanners

Year	Hedonic: Pooled Unweighted	Hedonic: Pooled Weighted	Hedonic: Adjacent Unweighted	Hedonic: Adjacent Weighted	δ'_t
1974	+0.09	+0.15			
1975	-0.28	0.00	-0.09		
1976	+0.08	-0.09	+0.10	+0.04	-0.73
1977	-0.11	-0.06	-0.10	-0.05	-0.09
1978	-0.21	-0.51*	-0.26	-0.43*	-0.61
1979	-0.30	-0.09	-0.17	-0.03	+0.07
1980	-0.12	+0.03	-0.19	+0.09*	+0.12
1981	-0.02	-0.03	-0.02	-0.04	-0.04
1982	+0.06		+0.06*		+0.02

4.b Body Scanners

Year	Hedonic: Pooled Unweighted	Hedonic: Pooled Weighted	Hedonic: Adjacent Unweighted	Hedonic: Adjacent Weighted	δ'_t
1975	+0.04	+0.06	+0.04	n.a.	n.a.
1976	+0.07	+0.05	+0.05*	+0.04*	-0.81
1977	-0.09	-0.03	-0.02	+0.02	-0.56
1978	-0.03	-0.01	-0.00	+0.01	-0.02
1979	-0.03	-0.03	-0.01	-0.03	-0.19
1980	-0.05	+0.03	-0.06	+0.01	-0.10
1981	+0.09*	+0.08*	+0.08	+0.07	-0.19
1982	-0.05	-0.09	-0.12	-0.14	-0.19

* Yearly differences statistically significant ($\alpha = 0.05$ or better).

Table 5

Comparing Various Indices: All CT Scanners

Year	Nominal Index[a]		Hedonic[b]		ΔW-based	
1973	10,000		10,000		10,000	
1974	11,940		10,770		800	
1975	12,000		6,130		240	
1976	14,450		4,600		31	
1977	17,450	100	3,850	100	15	100
1978	15,940	91	3,050	79	13	87
1979	16,610	95	2,780	72	11	73
1980	20,190	116	2,840	74	10	67
1981	24,840	142	3,020	78	8	53
1982	25,940	149	2,730	71	7	47

[a] $\bar{p}_t \,/\, \bar{p}_{73}$, where $\bar{p}_t$ is the weighted mean price in year t.

[b] The Hedonic Index is based on the weighted pooled hedonic regression.

advance that took place in CT: the ΔW-based index goes down from 10000 to 7, implying a staggering real price reduction of 55% per year on average![17] It is important to note that, if one were to start the measurements say, in 1977, the extent of the discrepancies would be greatly attenuated, as can be infered from the figures in italics in table 5. However, rather than finding comfort is those figures, they should serve as a warning, i.e. the hedonic method may not do so badly when it comes to technologically mature industries, but it seems to be completely off mark early on, when it is needed the most.

Going back to tables 3 and 4, it is interesting to contrast the relative performance of the hedonic index for head versus body scanners. Notice that, starting in 1977, the hedonic indices for head scanners based on weighted regressions do not diverge that much from δ'. On the other hand, those for body scanners do extremely poorly, except for two years (1978 and 1982). This is no coincidence: as said before, even though there were some improvements in the attributes of head scanners after 1977, most of the 'action' in that segment of the market took the form of downward displacements of the hedonic price function, i.e. price reductions for only slightly altered systems. As argued in section 4.2, the hedonic technique is indeed quite appropriate in that case. Body scanners, on the other hand, kept getting better and more expensive (in the terms of section 4.2, that would correspond to 'extending

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[17] Of course, the impact of such a dramatic price drop on any aggregate price index (such as the PPI) will depend upon the share of CT scanners in that index, which will quite certainly be very small. Just to give some idea of the effect of aggregation, consider the following: CT scanners belong in the PPI to the 9-digit category 11790514 ("Diagnostic electromedical equipment"), probably with a share of 10-15%; this category is in turn part of "Electrical machinery and equipment" (117), which has a weight of 5% in "Capital equipment", which in turn constitutes just about 25% of the PPI.

the range'), a phenomenon that completely eludes the hedonic method.

Fundamentally, the reason for the striking divergence between the hedonic and the ΔW-based indices has to do with discreteness: as any other Divisia-like index, the one based on the hedonic price function presumes that the changes that are being tracked happen continuously, or at least in sufficiently small steps. Clearly, that cannot be held to be true in the case of CT: first, the choice set consisted of relatively few and non-contiguous brands, and second, the technology evolved by leaps and bounds, primarily in the form of the appearance of new, much improved (and more expensive) systems. What makes a Divisia-like index wholly inadequate in this case, then, is the conjuction of these two aspects of discreteness, at least during the first years of the technology. As suggested above, the hedonic index performs better for the converse reason later in the product cycle, as brands proliferate and the pace of improvements slows down.

6. The "New Goods" Problem Reconsidered

Product innovation has been defined here in broad terms, including the introduction of new goods, increased variety, and changes in the qualities of existing brands. Actually, though, the measures ΔW_t as discussed in section 2 cannot be used to assess **directly** the introduction of new goods, in the sense of the first-time appearance of entirely new products that cannot be related to existing product classes, but span instead new classes of their own. The reason is that in order to compute ΔW_1 there has to be a reference set S_0 and a function W(S) to begin with, that is, something to compare the innovation to, and a yardstick to evaluate the difference in value between old and new. Clearly, neither exists in the case of entirely new goods. Given the prominence that the "new goods problem" has received in the literature, this might be regarded as a major drawback of the approach. I would like to argue that it is not so.

To begin with, I have suggested elsewhere (see Trajtenberg 1989) an indirect way of estimating the value of those radical innovations, that relies upon the dynamic interaction between innovation and diffusion. As described in the appendix, one can obtain an estimate for ΔW_1 as the answer to the question "how much had the introduction of the new good have to be worth in order to account for the first bunch of consumers that adopted the innovation and that would have adopted it even if no further improvements in the technology had taken place everafter?" In other words, find by backward extrapolation the ΔW_1 that would account for the original ceiling of the diffusion curve, considering that the ceiling rose later on as a consequence of further innovations. One could then use ΔW_1 to compute the real price change from period 0 to period 1, in the same way as for subsequent periods. Clearly, though, such estimate would be less reliable than those based on the later ΔW_t's, reflecting the inherent fuzziness that surrounds the valuation of breakthroughs.

However, regardless of how appealing this particular solution to the new goods problem might be deemed to be, I believe that the importance of the problem has been greatly exaggerated, thus diverting attention from the main issues. The reason is that the appearance of truly new goods (i.e. goods that cannot be analysed in the context of existing groupings) is in fact quite an infrequent event. The vast majority of product innovations that we actually observe take instead the form of quality improvements and increased variety within what can be safely regarded as given 'product classes'.[18,19] Moreover, the biases stemming from overlooking the strict new goods case are in all likelihood nil, simply because the quantities of new goods sold at the time of their introduction (during, say, their first year), are usually very small (see Diewert, 1987, and the appendix).

The perils of focusing nonetheless on the pure new goods case are obvious: since not much can be done about them, and since in any case their likely impact on real economic indicators would be nil, then (so this reasoning goes) one can just as well forget about product innovation altogether. Thus, for example, since we don't know (or cannot estimate with much precision) how much the first TV (or the first telephone, or the first CT

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[18] In traditional economic analysis, whereby agents supposedly confront a complete listing of perfectly homogenous goods, then all forms of product innovation are tantamount to the introduction of new goods. However, if one recognizes that there are natural commonalities between goods and hence that reasonable groupings can be formed, then there is a useful distinction to be drawn between the strict new goods case and other forms of product innovation. Where precisely to draw the line is of course an open (and very interesting) issue.

[19] This assertion might be met with some skepticism - after all, aren't we flooded with new products? Semantics aside (see previous footnote), the answer is **no**: how many product classes can one enumerate, and how many of these appeared, say, in the last decade? (as an exercise, try counting new household appliances). On the other hand, most existing goods have undergone many improvements over time, each constituting a product innovation. If still doubtful, consider the following simple argument: suppose that there are n_t different goods in the economy, and that a constant proportion of them, α, are improved every period (hence αn_t product innovations other than new goods occur per period). If the appearance of new goods had to match that, the number of new goods, m_t, would have to grow exponentially over time: $m_t = \alpha(1+\alpha)^{t-1}n_o$, which is clearly far-fetched, however generous one is in defining new goods.

scanner) was worth to consumers, let us not lose sleep if we ignore the long sequence of improvements in television technology that have occured since. Hopefully this paper will help disuade us from such unfounded complacency.

7. Concluding Remarks

This paper offers a way of tackling the long standing problem of quality change, that is both doable and well grounded in welfare economics. On the other hand, it is important to note the problems that its implementation is likely to pose. To begin with, ΔW-based indices require large amounts of data (particulary of sales per brand) that are difficult to come about. This is true for any particular product class, and obviously much more so if one were to apply it to a significat number of items in any aggretate index. Second, the actual computation of the ΔW's may raise issues that are hard to resolve unambiguously, and that could affect the absolute size of the gains (as opposed to their time profile, which is more likely to be robust).[20] Since the proposed indices do depend upon the absolute magnitudes of ΔW, some measure of arbitrariness might remain. Third, the method requires some non-trivial econometrics (as opposed to just arithmetics, as with current price indices), a fact that is likely to be met with strong resistance.

What all this amounts to is that the question that we have posed (namely

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[20]For example, I found in the case of CT that the coefficients of the MNL (and hence of $W(\cdot)$) changed from year to year, and therefore ΔW could be computed in two alternative ways: "ex-ante", that is, with the coefficients of the base year, or "ex-post". The two yielded different results - those reported in section 5 are based on the "ex-ante" calculations, for reasons discussed extensively in Trajtenberg (1990), chs. 3 and 4. Likewise, ΔW is very sensitive to the estimate of the marginal utility of income, α; how to get accurate estimates of this key parameter is open to question.

how to capture the welfare impact of product innovation in quality adjusted prices) is very hard, and calls for significant departures in data and method from current practice. It is still important to know how to do it (and how much we may be missing if we don't) whether or not we decide to commit significant resources for that purpose.

Appendix: Estimating the ΔW from the Introduction of a New Good[21]

The basic idea is to estimate a diffusion model as a function of time (associated with traditional demonstration effects), and of the cumulative gains from innovation, $CW_t = \Sigma_{\tau}^{t} \Delta W_{\tau}$ (notice that $CW_1 = 0$, where $t = 1$ refers to the time when the new good is introduced). The latter are supposed to track the reduction in real prices that trigger adoption by inframarginal consumers. Consider for example the following logistic model,

$$F(t) = [K_o + kCW_t] / [1 + \exp(\alpha - \beta t)]$$

where $F(t)$ stands for the cumulative distribution of adopters, K_o for the initial value of the ceiling, k measures the impact of innovation on diffusion, and α and β are the traditional logistic parameters.[22] Thus, if no innovations were to occur following the introduction of the new good then only K_o percent of potential consumers would adopt the product over its entire diffusion path. However, if $k > 0$, then succesive improvements in the technology will shift this ceiling upwards. Having estimated K_o and k one can then ask, what would the value of the first appearance of the good had to be in order to bring K_o percent of users to adopt the new technology? The answer is simply $\hat{\Delta W}_1 = \hat{K}_o / \hat{k}$, that is, the model as formulated above is

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[21] See Trajtenberg (1990), ch. 4, for a detailed discussion.

[22] Of course, the ceiling need not be linear in CW, and if innovation persists over long periods of time, it could not be (certainly not if one were to use the equation for prediction). I use here the linear form just for simplicity.

equivalent to one where K_0 is deleted and CW_1 is set equal to $\Delta\hat{W}_1 = \hat{K}_0/\hat{k}$ rather than to zero. In the case of CT the estimated equation was (asymtotic standard errors in parenthesis)

$$F(t) = [\underset{(.003)}{.074} + \underset{(.002)}{.025}\, CW_t] \,/\, [\underset{(.07)}{3.44} - \underset{(.001)}{.06}\; t], \qquad RSS = .006,$$

meaning that, had technical change ceased after the introduction of CT in 1973, only 7.4% of hospitals would have adopted it in the long run. In fact, the ceiling had climbed to 49 percent by 1982 as a result of the flow of innovations from 1974 on, since every million dollar worth of improvements shifted the ceiling by 2.5 percentage points (CW_{82} = 16.6, and hence K_{82} = 0.074 + 0.025 x 16.6 = 0.49). This renders a value for the introduction of CT of ΔW_{73} = 0.074/0.025 = 2.9 million $. Since the price of the first scanner was $ 310,000, the real price change associated with the appearance of CT scanners would be δ' = -0.91. However, given that a mere 16 scanners were ordered in 1973, the impact of this initial price drop on any aggregate price index would be nil.

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