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8 From Superminis to Supercomputers: Estimating Surplus in the Computing Market

Shane M. Greenstein

8.1 Introduction

Innovation is rampant in adolescent industries. Old products die or evolve and new products replace them. Each new generation of products offers new features, extends the range of existing features, or lowers the cost of obtaining old features. Vendors imitate one another's products, so that what had been a novelty becomes a standard feature in all subsequent generations. Depending on the competitive environment and the type of innovation, prices may or may not reflect design changes.

The computer industry of the late 1960s and 1970s experienced remarkable growth and learning. At the start of the period several technological uncertainties defied easy resolution. Most knowledgeable observers could predict the direction of technical change, but not its rate. Vendors marketed hundreds of new product designs throughout the 1970s, and a fraction of those products became commercially successful. In time the industry took on a certain maturity and predictability. By the late 1970s, both buyers and sellers understood the technical trajectory of the industry's products. Even the least experienced

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users understood the capabilities and limits of the most popular commercial systems.

This paper attempts to measure the economic benefits that accrued to buyers from technological innovation in the computer industry. Its thesis is that many innovations that created economic value in this period are associated with extensions in computing capabilities, as distinguished from declines in prices which occurred at the same time as the extensions. This paper does not argue that price decreases were unimportant to buyers, but that price decreases alone tell an incomplete story about the welfare improvements realized by buyers.

This thesis goes to the heart of the relationship between rapid "constant-quality" price declines and the inferred improvement in economic welfare. The open issue concerns whether constant-quality price indexes provide the same information about the experience of a buyer who continues to buy computer systems with a similar set of characteristics as about that of a buyer who takes advantage of the availability of characteristics that did not previously exist. There are reasons to think constant-quality price indexes do not provide the same information on both types of buyers. The correspondence between constant-quality price indexes and economic welfare will be weaker when product characteristics cannot be repackaged (e.g., see Trajtenberg 1990). For example, one large computer system may provide more services to a buyer than two systems with exactly half the measurable characteristics. The appropriate welfare issue concerns buyer satisfaction with the extension of product space—that is, the extension of the range of quality available. If a set of adopters of new products could be accurately surveyed, how much would they be willing to pay not to give up the new capability associated with extensions of computers? A large body of work on cost-of-living indexes suggests that the "willingness to pay" for product extensions may have a nonlinear relationship to constant-quality price decreases.[1]

The problem considered here does not lend itself to a single statistical test or experiment. To reach a convincing conclusion, it would be better to see if a variety of information sources point in a similar direction. This paper addresses several related questions. First, what innovations in this period are associated with extensions of capabilities? Second, do buyers adopt products that embody extensions of capabilities? Third, how could a measurement framework represent that action? Are extensions embodied only in increases in capacity or other measurable features of a computer system?

Many of these questions require an explicit supply and demand framework.

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[1] It is well known that there are problems with using price indexes to measure the benefits associated with new goods. The same problems arise if extensions of product space (e.g., inventing a system with computing capacity that is twice as high as any previous system's) are associated with new services. In either event, there is an important issue regarding the procedures for incorporating new goods into price indexes. As Triplett (1989) argues, the central issue in developing appropriate procedures revolves around the goals of the index: whether it intends to reflect changes in the "costs of producing" or changes in the "costs of living." This paper focuses primarily on issues regarding the measurement of changes accruing to buyers.

The difficulty here concerns the fit of a framework to a differentiated-product industry; inevitably, some features of reality are sacrificed to a model. This paper modifies a Bresnahan-Berry model of vertical quality differentiation, which differentiates products along only one dimension, here, computing power.[2] While simple, this specification captures much of the difference in demand for systems with different computing capacities, that is, measurable changes in demand for systems with higher speed and more memory. The paper argues that changes in capacity provide information about the introduction of new capabilities and services. Thus, the model quantifies important extensions in product space over time and the contribution to surplus from these extensions. In addition, the model estimates the decline in the cost function of computer vendors over time, which serves a secondary goal, namely to estimate a fully specified model of the computing market in which changes to the costs of producing quality alters market outcomes. Finally, though the model predicts intersystem competitive outcomes with only limited success, it provides a rough measure of the importance of new-product entry for buyer's surplus.

8.2 Technological Changes in Computing, 1968–1981

This section briefly describes important features of technological change in the mainframe computing market from 1968 to 1981. During this period the industry witnessed a rapid decline in prices, a dramatic extension of capabilities, and a notable change in the quality of alternatives to mainframes. For some buyers the economic benefit associated with technological change in mainframes was declines in prices, for others it was extensions of capabilities. Each is discussed in turn.

Over the long run, mainframe products underwent a rapid decline in prices per measurable unit of computing, usually measured by central processing unit (CPU) speed and memory capacity. The important open debate concerns the association of dramatic change in price per computing unit with the introduction of particular products and other market events.[3] For example, there is no

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[2] All previous research investigates automobile-producer and -buyer behavior (Bresnahan 1981, 1987b; Feenstra and Levinsohn 1989; Berry, Levinsohn, and Pakes 1993). Previous use of these methods required a complete census of the price, quantity, and characteristics of every product in the market. The methods developed in this paper can be used when a complete census of product characteristics is not known, which suits data typically available to a computer-industry researcher.

[3] Construction of constant-quality price indexes has received much attention because of its importance for gross national product (GNP) measurement. There is much disagreement about the proper methods to use and the proper data to employ to measure this phenomenon. See Gordon (1989, 1990); Dulberger (1989); Cole et al. (1986); Triplett (1986, 1989); Berndt and Griliches (1993); Berndt, Showalter, and Woolridge (1991); and Oliner (1993). Related research on the welfare benefits from technical change uses similar price indexes to recover surplus generated from declines in the price of aggregate computing capital. Sometimes this approach also requires measurement of willingness to pay for new capabilities, which is often difficult to obtain (e.g., see Bresnahan 1987b; Flamm 1987a, 1987b; Brynolfsson 1993).

agreement about the improvement over previous generations associated with the introduction of the IBM system 370. This disagreement is important for any calculation of economic welfare because the system 370 replaced the system 360, and each was the most popular system in the United States in its day. Second, and more generally, the prices of old and new generations of systems, which may be substitutes, do not follow a simple pattern. Some observers argue that "disequilibrium" influenced the pricing of mainframes, though there is much disagreement about its root causes (Fisher, McGowan, and Greenwood 1983; Dulberger 1989; Gordon 1989). This debate influences the interpretation of the technical improvements embodied in new and old models. Both issues are discussed below.

The industry also experienced extensions in capabilities in many dimensions. Some improvements are reflected in the easily measurable features of a system, particularly those extensions associated with increases in computing capacity. Larger computing memory and faster CPU speeds permitted users to address increasingly complex problems and to perform regularly tasks that could not previously be attempted, let alone accomplished. Scientists and engineers were the first to take advantage of faster computing speeds and larger memories. Internal and external storage capacity also expanded, and input/output speeds increased. These innovations made large databases easier to use and broadened their potential applicability. Hardware architecture and operating-system software underwent many refinements associated with multiuser systems, a development crucial to all timesharing applications and applications that require many users to perform quick queries of centralized databases. Service bureaus, insurance and banking users, and many large organizations employed these developments in new inventory and reservation systems. Later refinements required quick access to large databases in real time. These applications were diffused widely in the 1960s, and the refinements began to be diffused in the mid-1970s (Fisher, McGowan, and Greenwood 1983; Flamm 1987a, 1987b).

Other extensions were also very important but are not so easily associated with measurable features of a system. Solid-state circuitry, improved air-conditioning units, and more-compact designs also made systems more reliable and lowered servicing costs, which resulted in the expansion of computing into ever more essential enterprise functions. New and better programming languages also diffused across many systems. By the end of the 1970s a third-party software industry had begun to mushroom, further diffusing refined application software across many computing platforms. Other peripherals also improved, such as printers, terminals, and countless other minor components. The relevant point is that these innovations and many others were important to buyers but are not easy to measure.

As the computer industry matured, users came to expect change—that is, extensions of capabilities or entirely new products—and plan for it. Buyers modified the memory and speed of their CPUs but kept other durable investments in software or peripherals. Or buyers enhanced particular software programs or peripheral components, but not other parts of their systems. As buyers learned about their needs and discovered technological opportunities, as new products were introduced, and as old products became obsolete, buyers had to continually reevaluate their situations. A regular cycle began to emerge: peripheral and software upgrading induced bottlenecks in CPUs, which induced further CPU upgrading, which induced further peripheral and software enhancements. The introduction of timesharing and techniques for querying central databases further accelerated these regular cycles.

Three important points follow from this cycle: first, upgrading to a larger CPU capacity became associated with taking advantage of technical improvements in other parts of the system. Thus, the invention, and reduction in price, of large computing capacity enabled many users to take advantage of technical change in complementary components. For many buyers, demand for greater computing capacity reflected demand for complementary peripherals and software. Second, the extension of capabilities in peripheral components, software, and CPUs interacted with enhancements in other parts of the system. The economic value created by the extension of computing capacity, while obviously important, does not relate in any linear fashion to the decline in prices in constant-quality CPUs. Value creation must also relate to the prices and functions of other parts of the system.

Third, the rate of value creation to a buyer could be much different than the rate of price decline in computing capacity. It could be faster if declines in prices enabled a user to realize local economies of scale in the distribution of computing services and in the employment of computing capital investments. Localized economies of scale could produce the repackaging problem in CPU product characteristics, that is, buyers valued the increase in computing capacity embodied in CPUs. Since researchers of centralized management of computing facilities (e.g., Inmon 1985; Friedman and Cornford 1989) emphasize the replacement cycle, this factor was probably very important for many buyers. On the other hand, the rate of value creation to a buyer could be slower if the bottlenecks underlying the replacement cycle choked off the ability to realize much advance. Since researchers of centralized management of computing facilities also emphasize increasing buyer dissatisfaction with translating enterprise needs into feasible technical solutions, particularly by the early 1980s, many buyers may not have realize localized economies of scale.

Notable changes to nonmainframes partially determined the relative value buyers placed on the changes to large systems. If some buyers do not have a repackaging problem, declines in prices may simply induce purchases of cheaper computing power, but not necessarily purchases of bigger CPUs. That is, the choice between a large or a small CPU depends on the relative price per characteristic for small and large systems as each is introduced. This is important because there were many changes in these choices over the period. Few general-purpose computing substitutes for mainframes were available in 1968, but over the 1970s minicomputer hardware along with general-purpose software was developed, so that users could perform some small tasks that previously required mainframes. These minicomputers were especially attractive for a decentralized computing environment. By 1981 minicomputer vendors were also beginning to offer users viable growth paths for their systems if the users' needs outgrew large superminis.[4] In principle, buyers could (and many did) break up their computing needs into smaller units, taking advantage of decentralized management. Most importantly for empirical purposes, the costs and capabilities of smaller systems shifted over the period, and their purchase is outside the view provided by the data in this paper.

This brief history suggests that it may not make sense to conceive of technological change as equivalent to a simple fall in price levels. Price declines enabled many events that took place. Yet, important episodes of value creation were associated with specific inventions that extended buyer capabilities into new areas—for example, the invention of reliable real-time database querying or the invention of interruption-free multiuser computing. Value creation was not associated solely (or even primarily) with the decline in costs of the delivery of these services. The willingness to take advantage of new capabilities in any period became associated with a willingness to adopt computing capacity of higher and higher levels. The importance of the willingness to pay for new capabilities will ultimately be an empirical issue. Is there evidence of much adoption of systems with increases in capabilities?

8.3 The Model

A supply-side model and a demand-side model constitute this paper's measurement framework. The model focuses attention on the demand for computing capacity. The model is flexible enough to allow underlying demand preferences to vary over difference capacities and sizes and to change over time. It also permits the costs of supplying computing capacity to decline over time. Finally, it provides a rough test of whether vendors compete solely in measurable features of computing capacity.

8.3.1 Demand-Side Considerations

Consider a market in a given year. As in Bresnahan's (1981, 1987a) model of the automobile market, this study makes five assumptions: (1) All users evaluate all mainframe computers in terms of the same (vertical) index of quality, that is, computing power. (2) Users differ in their willingness to pay for computing power. (3) There are many "uses" for computer systems, each requiring one computer system. (4) Each potential user compares N possible

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[4] Note that personal computers (PCs) were only beginning to diffuse by 1981 and were largely employed as sophisticated terminals. PCs were not viewed as substitutes for mainframes except for very small problems.

different models. The net benefit from each model j in use i is $U_{ij} = e_i d_j - P_j$. Here, e is the marginal utility of quality, which varies across users i, d is quality, and p is the price of the product. (5) There is a composite good of "lower" quality, which is not part of the focus product group but is a potential option for purchase by users. This will be good zero, the "outside good." It sells for price P_0 and has quality d_0. In this study, the outside good is equivalent to a small IBM mainframe or general-purpose superminicomputer. Its price and quality change each year.

Equilibrium in the market concerns the demand for computing power. The system chosen satisfies $U_{ij} > U_{ik}$ for all j, $k \neq j$. Thus, an optimal choice implies that $e_i > b_{jk} = (P_j - P_k)/(d_j - d_k)$ for all j, $k \neq j$. In equilibrium, users will find that they can rank systems (see Bresnahan 1981 for elaboration) according to their computing power. All j models are ranked according to d_j or P_j; either ranking is equivalent in equilibrium.[5] Some systems will provide considerable computing power but will be expensive, while others will provide little computing power but will be inexpensive. The data in this study appear consistent with this structural assumption for two reasons: (1) a spread exists between the capabilities (and prices) of the least and most powerful mainframes, and (2) most measures of computing performance and prices are highly correlated.

Let the willingness to pay for computing power, e_i, be distributed according to some function $F(z)$. This function represents the cumulative distribution of purchasers with a marginal utility of purchase less that z. Let S_j measure the market share of product j. Model $j = N$ is the highest quality available, and b_j measures a choice between j and $j - 1$. This implies $b_j = F^{-1}[1 - (\Sigma_{k=j}^{N} S_k)]$, $j = 1, \ldots, N$, where $S_j = Q_j/M$, Q_j is the quantity sold of product j, and M is the total potential size of the number of uses. If M is a parameter to be estimated and Q is data, then by design $0 < \Sigma_{j=1}^{N} S_j \leq 1$, so $M > \Sigma_{j=1}^{N} Q_j$, since the outside good is not observed. That is, estimates of M, the total size of the market, must exceed the total number of observed purchases.[6] As in Bresnahan (1981, 1987a), this paper also employs a uniform distribution, $b_j = [1 - (\Sigma_{k=j}^{N} S_k)]$. Thus, estimating the density is essentially the same as estimating M.[7] This is illustrated in figure 8.1. The above implies a relationship

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[5] In this model $d_j > d_{j-1}$ implies $P_j > P_{j-1}$ for all observed j systems, since a system violating this inequality would not be chosen at all. Thus, prices must rise faster than quality as quality improves. Increasing the marginal costs of quality can yield this outcome. See Bresnahan (1981, 1987a) and Berry (1994) for further elaboration.

[6] Previous authors have assumed that M was known, so estimating M is one novelty here (Berry 1994).

[7] Berry (1994) suggests using distributions other than the uniform. With an exponential distribution we get $b_j = -\Theta \ln[S_j + \exp(-b_{j+1}/\Theta)] = -\Theta \ln(\Sigma_{k=j}^{N} S_k)$, where Θ is the mean of the exponential distribution. This must be set equal to one, since it is not identified. Preliminary research also used an exponential distribution and found no change in the essential results, so this paper will only show results for the uniform distribution. For the price and quantity data used in this paper, estimates of implied quality with the two distributions were highly correlated in every year of this sample (around .9).

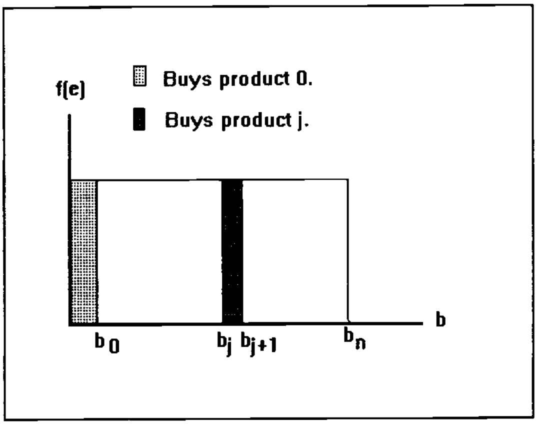

Fig. 8.1 Determination of market share in a vertical model

between market share and quality, that is, $d_j = d_{j-1} + (P_j - P_{j-1})/b_j, j = 1, \ldots, N$. To adapt to an incomplete data set (explained below), take the definition for b and substitute recursively to get

$$(1) \qquad d_j - d_0 = \sum_{k=1}^{j} \left\{ (P_k - P_{k-1}) / \left[1 - \left(\sum_{h=k}^{N} S_h \right) \right] \right\}.$$

The model has several noteworthy features. First, equivalent prices between models j and $j + 1$ imply equivalent qualities. Second, the value of $d_j - d_0$ is the net quality of a system compared with an outside good. Without a measure of the quality of the outside good, it is only possible to directly compute an index of a system's quality compared with an (unobserved) outside good. This makes for careful interpretation because the price and quality of the outside good are changing over time. Third, computing $d_j - d_0$ does not require any data on system characteristics, only data on prices and quantities. It is entirely a function of the total estimated users and the data about the prices and market shares. This will suit available data well, because there is acceptable information on prices and quantities but not on every system's characteristics.

8.3.2 Supply-Side Considerations

There are many optional forms for describing supply-side behavior. The simplest is the case of independent pricing. This model assumes that the economic actor who prices a system only considers the effect of a system's price on the profitability of that system and does not internalize the effect of that system's price on the profitability of any other system. Marginal revenue equals

$$(2) \qquad MR_j = P_j - S_j / \left\{ \left[1 - \left(\sum_{h=j}^{N} S_h \right) \right] / (P_j - P_{j-1}) + \left[1 - \left(\sum_{h=j+1}^{N} S_h \right) \right] / (P_{j+1} - P_j) \right\},$$

where this expression takes advantage of the definition of b_j in terms of prices and implied qualities.[8]

The independent-pricing model easily generalizes to a conjectural-variation model (Bresnahan 1989), an approach widely used in empirical applications for testing behavioral assumptions.[9] The conjectural-variation parameter tests the assumption of Bertrand pricing, which is roughly equivalent to testing whether some unobserved factor other than demand for computing capacity influences prices. Marginal revenue is

$$(3) \qquad MR_j = P_j - \exp(\delta)Q_j/M[(d_j - d_{j-1})^{-1} + (d_{j+1} - d_j)^{-1}].$$

It is easier to estimate exp(δ) than v, because it prevents accidental division by zero in a maximum-likelihood algorithm. Testing Bertrand behavior amounts to testing $H{:}\delta = 0$. If δ is large, then v is close to 1 and Bertrand pricing is rejected. The demand elasticity for system j is $e^j_{QP} = -P_j g(P,Q,M)/\exp(\delta)S_j$. Notice that M and exp(δ) are the only estimated parameters in MR and e^j_{QP}, which means many factors influence the estimate of M. This is important because the bounds on the estimate of M, $M > \sum_{j=1}^{N} Q_j$, limits the elasticity. Since exp(δ) acts in inverse relation to M, estimates of δ may offset limits associated with estimating M.

This model of vendor behavior has several obvious drawbacks. Independent pricing violates the spirit of multiproduct competition in the mainframe computer industry.[10] Moreover, the above specification is not ideal for modeling the pricing of older systems, where the used market constrains pricing (Oliner 1993). Finally, the above specifications do not treat vendors asymmetrically, which violates industry folklore about IBM's dominance. These are important issues for the estimation of vendor behavior, though not necessarily important for the estimation of buyer's surplus, nor necessarily for quantifying extensions in product space. The discussion of results will highlight the points at which these issues pertain to this study's analysis.

8.4 Estimation

Berry (1994) compares the computed implied quality with measured quality and the implied marginal revenue with measured marginal cost, which is the strategy used here with modifications to match available data. The measures of quality are the vector x_j for product j. Then

$$(4) \qquad \begin{aligned} d_j - d_0 &= \exp(x_j\beta + \varepsilon d_j), \text{ and} \\ MR_j &= \exp(x_j\alpha + \varepsilon s_j), \end{aligned}$$

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[8] Note that marginal revenue must be suitably adjusted when $P_j = P_{j-1}$, which is a rare event in this data. This paper adopts the convention that both systems compete against their nearest neighbors. Thus, the marginal benefit from changing a price is from cutting into that neighbor's market share.

[9] See the discussion in Bresnahan (1987a) for more on this point.

[10] This experiment cannot employ Bresnahan's (1981) approach to this issue because in this paper's data it is very uncommon for the same firm to market two "neighboring" products.

where εd_j and εs_j are error terms. The multiplicative form for the quality index is for convenience. The multiplicative form for marginal cost, following previous research (e.g., Bresnahan 1981, 1987a), assumes that marginal costs are convex in characteristics. It also guarantees positive estimated marginal costs. It is necessary to instrument for x_j since the cost of designing systems with x_j characteristics determines the observed characteristics and their prices (and quantities and implied quality), leading to simultaneous-equations bias.

Note that d_j is an implicit function of M and P_0. This analysis assumes M is unknown and P_0 is known, with one exception described below.[11] Let $M = TQ(1 + r)$, where $TQ = \Sigma_{j=1}^{N} Q_j$ is the total number of observed purchases. This analysis assumes $r_t = r_{t+1}$ for all t, but otherwise there will be separate supply and demand equations for each year in the initial estimates.[12] As described below, the data are arranged to determine P_0 in each year. This benefits the simulations later and does not significantly change estimation results.[13]

When M and the other parameters are not known, they can be estimated using nonlinear three-stage least squares (Amemiya 1985). Minimize

$$f = \varepsilon'(\sigma \otimes P_z)\varepsilon, \tag{5}$$

where $\varepsilon = Y - (X'P_zX)^{-1}X'P_zY$, $P_z = Z(Z'Z)^{-1}Z$, $Y' = (d', MR')$, d and MR are vectors of the left-hand-side variables, x is the matrix of regressors, X is a block diagonal matrix of regressors x, z is a matrix of the set of instruments for x, and Z is a block diagonal matrix of instruments z. The choice of x and z will be discussed below. Note, however, that this system can be estimated since there exists a complete set of data on prices and quantities. There is no need for x variables for every system's characteristics. The σ term is a two-by-two matrix of consistent estimates for the variance and covariance of ε. These estimates are found from the nonlinear two-stage least squares errors and are equal to $\sigma = \Sigma(\varepsilon'\varepsilon)/T$, where T is the number of observations. Minimizing the above equation yields estimates for α, β, and M, which then yelds estimates of $d_j - d_0$ and elasticities.[14]

There is a subtle tradeoff between guaranteeing positive estimates of mar-

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[11] If M is known, then it is easy to estimate the independent-pricing model. P_0 can be left unidentified within a constant term. Thus, one can estimate $\ln(d_j - d_0 - x_j\beta = \varepsilon d_j$ and $\ln(MR_j) - x_j\alpha = \varepsilon s_j$ using a standard minimum-distance estimator.

[12] Other parameterizations of the size of the market did not produce qualitatively different results, so this paper only presents the simplest specification.

[13] Without further economic modeling of the outside good and its quality, d_0, the structural form for P_0 will necessarily be ad hoc. Bresnahan (1981, 1987a) deals with this issue by positing a hedonic relationship between the quality of the outside good and its price.

[14] In practice, minimizing f can be very time consuming. Effort is saved by recognizing that the optimized estimated β and α will be $[\alpha,\beta]' = [X'(\sigma\otimes P_z)X]^{-1}[X'(\sigma\otimes P_z)Y]$. Setting β and α equal to optimized values and substituting into f yields a concentrated function determined solely by the value of M and market-power parameters. It is then straightforward to find the optimal α and β (as functions of the optimal d and MR). The final step is to find the standard errors for all the estimates by computing the variance-covariance matrix with all the (already optimized) parameters.

ginal costs and guaranteeing plausible elasticity estimates for every product. If marginal costs are positive by design, marginal revenue may be negative for a few observations where parameter estimates are "far away" from their respective optimums. This is problematic because it destroys any maximum-likelihood algorithm (i.e., $\ln[MR]$ does not exist for $MR < 0$). The more general point is that the functional form cannot guarantee that all product elasticities are less than -1 at nonoptimized parameters. This is related, since $MR_j = [P_j(1 + 1/e_j)]$.

The approximation $\ln[P_j(1 + 1/e_j)] \approx \ln(P_j) + 1/e_j$ eliminates both problems and results in positive marginal costs everywhere. This works well with this paper's data because $1/e_j$ is much less than -1 for all but a few observations in the final estimates. The alternative solution to the above problems, which is not presented, is to not guarantee that marginal costs are positive. This alternative lets elasticities attain both plausible and implausible values without stopping the whole estimation, but it sometimes results in negative predicted marginal costs. Since a few implausible elasticities are inevitable under either specification, at least the approximation above guarantees positive marginal costs. As it turned out, all but a few elasticities were much smaller than -1 at optimized parameters, so the cost of using the approximation was small.[15]

8.5 Surplus Measurement

The total buyer's surplus net of the outside good is

$$(6) \qquad \sum_{j=1}^{N}[(b_j + b_{j+1})(d_j - d_0)/2 - (P_j - P_0)]Q_j.$$

Since d_0 is not identified, d_j alone cannot be identified. The $d_j - d_0$ can come from two possible sources. If there is characteristic data for all systems, then it is possible to use the estimate of β and x_j. Since this paper does not have data for all systems, $d_j - d_0$ come directly from the estimate of M and from the data on prices and quantities.

This method does not measure the benefits from buying a system in terms of its characteristics. Nor does it measure the average benefits from buying a system, or the total benefits to buyers from computerization. There are two reasons for this. First, this model of each year's competition presumes to measure the benefits associated with the last bit of computing power purchased, not the surplus associated with buying the first fractional unit of computer

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[15] One other alternative is to use an error structure like the one found in Bresnahan (1981, 1987a). He solves for the optimal price and quantity under the assumption that the model is correct and compares those computed numbers against the actual observed data. Bresnahan's alternative requires a complete data set, i.e., characteristics for all models. While this exists for new automobiles, such data do not exist for the historical computer market, rendering this alternative infeasible.

power. Second, the method does not anchor the estimates of the quality of a system over time. That is, the absolute level of quality of a particular model is not constrained to be similar over time. Thus, surplus estimates may change over time due to changing units of comparison. In particular, the outside good changes each year, altering the relative benefits of being in the mainframe market.

These limitations make the method well suited to two unit-free estimates of the importance of new entry. One is to estimate the percentage of surplus in a given year attributable to systems with certain features, such as young age or large computing power. The main advantage of this measure is that the percentage of surplus is unit-free and easily compared over time. If extension of capabilities matters in this market, then it must at least hold in the single capability extended here, computing power. If the percentage of surplus associated with large systems falls over time, then we reject the view that this factor matters.

A second experiment involves removing systems with particular characteristics and comparing surplus generated with and without those systems. This comparison is in the spirit of welfare calculations that hold population and demand characteristics constant but change the choice set available to consumers. As before, the percentage difference in surplus is unit-free and easily compared over time. If buyers adopt new systems because they embody unobservable, but valuable, extensions of capabilities, then removing new systems could result in large losses in surplus.

8.6 The Data

This paper's data on computer prices, quantities, and vintages come from industry censuses from International Data Corporation's (IDC's) Electronic Data Processing Industry Reports (EDP/IR).[16] IDC estimated the number of installations of each type of computer system and, until 1981, estimated the monthly rental at which an average type of system leased.[17] The data in this paper begin with the 31 December 1968 report and end with the 1 January 1981 report. The first year in which IDC distinguished between the number of installations inside and outside the United States was 1968. Over the entire fourteen-year period, these data concern the installed base of over 350 different

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[16] Patrick McGovern began compiling this census in 1962 in *Computers and Automation* magazine. It continued in modified form under IDC auspices from the mid-1960s onward. The archives of the Charles Babbage Institute at the University of Minnesota contains a collection. This paper also makes use of a set of EDP Industry Reports contained at the Library for the Graduate School of Business at Stanford University.

[17] Phister identifies several years in which IDC revised the reported number of installations in previous years, particularly for IBM models in 1967–72. In those cases, Phister's reported updates were used. This makes this paper's estimates comparable with Phister's (1979) and Flamm's (1987a, 1987b) descriptions of the diffusion of computing equipment, which used more-aggregate IDC data. It also makes this paper's results comparable to Oliner's (1993) analysis of the retirement patterns among IBM mainframes, which uses similar IDC data for IBM systems.

computer systems (see the appendix of Greenstein 1994). These are clearly the best data available on the size of installed base and rental prices.[18]

8.6.1 The Sample

Without modification, two biases arise from maintaining exclusive use of IDC's definition of a mainframe. First, the 1968–69 definition of a mainframe is too broad. It includes some systems that IDC reclassified as "digital dedicated applications" in 1970. These systems are actually minicomputers, like the Digital Equipment Corporation's (DEC's) PDP-8, not general-purpose systems. Second, more redefinition problems arise on a smaller scale because IDC established several on going databases for systems other than mainframes (i.e., minicomputers, small business systems, desktop systems). Its researchers occasionally move a system into the mainframe category that was not previously there. Its researchers also move a system out of the mainframe category that previously was there.[19]

The best solution to this problem defines the outside good consistently across different years of the sample. This paper's outside good is the smallest mainframe offered by IBM, a system 360/20 (introduced in September 1965). The system 360/20 has the virtue that it is very close to the smallest mainframe in IDC's census, but it provides a more consistent definition of the lower bound on this market over time than that used by IDC. Moreover, its price changes throughout the sample period, reflecting real changes in the quality and market price of systems that performed small decentralized computing tasks. Finally, it eliminates only a few useful potential observations in each year.[20] Table 8.1 shows the results of this selection. Consistently defining the outside good does not impose a large loss. The systems used by more than twenty thousand buyers typically are sampled. The greatest losses occur in the most recent years, when this procedure eliminates 12 of the 178 potential observations from IDC's census.

Even with a consistently defined outside good, two potential problems remain. First, IDC revised its survey scope twice, once between 1969 and 1970, and once between 1976 and 1977. In both cases, IDC consolidated the number of models it covered.[21] Second, by the end of the sample, the difference between mainframes and some large general-purpose minicomputers ("su-

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[18] No other comparable data source exists for this period. Remarkably, only a few studies of the computing market (e.g., Michaels 1979; Phister 1979; Flamm 1987a, 1987b; Dulberger 1989; Oliner 1993; Khanna 1994) have used parts of this data and none has ever exploited all facets of it (e.g., see Greenstein 1994 for an examination of diffusion).

[19] The most important case is IDC's decision to include the IBM system 36 in the sample in 1976 (estimated installed base at five thousand units) and exclude it from mainframes after that (but include it in "small business systems"). Early experiments showed that this particular flip-flop makes 1976 estimates inconsistent with those of other years.

[20] Part of the reason is that there are fewer characteristics data available for the small systems. In addition, the vast majority of eliminated systems were commercial failures.

[21] For example, the number of models covered in 1969 was 176, while only 147 were covered in 1970. In 1976 there were 205 models covered, but only 188 in 1977. See table 8.1.

Table 8.1 **Matching Industry Data with Characteristics Data**

Year	Sample of Installed Bases	Original Number of Models	Models with Characteristics Data	
			All	Included in the Sample
1968	19,361	166	59	53
1969	21,470	176	66	60
1970	25,233	147	72	64
1971	19,008	154	81	67
1972	21,909	171	95	77
1973	21,541	173	103	88
1974	22,253	181	113	96
1975	23,351	189	119	101
1976	23,673	205	133	113
1977	23,436	188	134	122
1978	25,124	205	148	136
1979	25,261	218	150	138
1980	24,723	244	167	155
1981	28,116	257	178	166

perminis") becomes blurred, which raises questions about the survey's completeness. The main issue is whether IDC included in the mainframe category all the superminicomputer systems that were close substitutes for general-purpose mainframes. A reasonable case could be made that IDC included most relevant systems,[22] but a reasonable case could also be made that it did not.[23] Ending the sample in 1981 holds this problem to a minimum.

8.6.2 Definition of Market Share and Price

The paper uses the installed base of systems in a given year as a measure of quantity and market share. This is justified because most buyers leased their

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[22] It is not clear whether the money spent on superminis ever amounted to more than a small fraction of the amount of money spent on mainframes. According to the 1983 IDC census for minicomputers and mainframes, the value of installed base associated with superminicomputers came to roughly half the value of all minicomputers, or roughly 15 percent of the value of the installed base of mainframes. IDC's census differs from the other censuses, particularly that of the Computer Business Equipment Manufacturing Association (CBEMA), because IDC includes several systems as mainframes (i.e., those from IBM) which others classify as superminicomputers. This makes IDC's census more "complete," which matters by the early 1980s. For example, according to CBEMA (1992), in 1976 mainframe shipments reached over $5 billion, while the total spent on all minicomputers was $1.8 billion. By 1982, CBEMA estimates that mainframe shipments reached $10.6 billion and minicomputer shipments reached $7.7 billion. CBEMA does not state what fraction went to superminicomputers, but $7.7 billion clearly overstates the size of the competition between mainframe and minicomputers.

[23] The most questionable omissions in IDC's mainframe tables are those regarding the VAX models from DEC, and similar competitive models from other firms such as Wang, Prime, and Data General.

equipment in the late 1960s and 1970s. Moreover, many mainframe computers are not subject to frequent mechanical breakdowns, so the services delivered do not physically depreciate rapidly after sale, if at all (though market value may depreciate due to technological obsolescence). The drawback is that this definition overstates the popularity of an old system (and the general competitiveness of the market) by showing that old and new systems are in competition.

While Phister (1979) clearly believes that IDC's estimates of installed base are the best among the available alternatives, he nevertheless warns about several potential problems that could influence calculations using these data.[24] Dulberger (1989) also questions the accuracy of IDC's estimates of installed base, while conceding that they are the best publicly available.[25] Given these concerns, the data were tested for internal consistency, which they readily met.[26] In any event, no alternative is satisfactory. Sales data are not available, and it is not possible to estimate sales from the change in installed base from year to year, because it becomes an increasingly poor estimate of shipments of systems when systems become more than a few years old.

IDC estimated the price of a typical system configuration, which is the price used in this study. IDC's estimates are probably of the right order of magnitude, but they are also subject to measurement error. Phister uses these prices for estimates of the value of installed base. However, he believes that the prices for obsolete systems are too high, since IDC would use the last offered price for a system lacking any recent transaction, but that the bias in old prices influences only a few of the systems in the United States. Flamm (1987b) reaches a similar conclusion before using Phister's estimates for a few calculations.[27] Thus, no strong conclusions should rely exclusively on one price.

8.6.3 System Characteristics

The characteristics that make up x_j partially overlap those used in Gordon's (1989, 1990), Dulberger's (1989), and Oliner's (1993) analyses of computer-system hedonic regressions (see Triplett 1989 for a complete summary of the relevant issues). MIPS, or millions of instructions per second, is an estimate

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[24] He states, "It is my opinion that IDC's staff, files, and data sources make that organization's published statistics the best available" (250). Yet, due to occasional revisions of previous EDP/IR reports, Phister is not convinced that IDC's estimates of the size of installed base are precise. However, many of his uses of these data reveal his belief that IDC got the order of magnitude correct. Where available, this paper uses Phister's corrections.

[25] One especially difficult problem is that IDC may underestimate the number of users who upgrade their systems (Dulberger, personal communication, July 1991).

[26] The history of each new system was examined. Did the development of its installed base follow a reasonable pattern of growth, i.e., several years of growth followed by several years of decline? The absence of such a pattern would have called into question the plausibility of the data.

[27] In addition, using these prices is not without precedent in the hedonic literature. The prices for new systems used by Gordon (1989, 1990), as well as by many others, are very similar to those used here. Gordon's prices for his sample after 1977 were taken from *Computerworld*, which is published by IDC.

of speed. The maximum memory in megabytes (MB) included in a system is an estimate of memory size.[28]

MIPS and memory-size data are not available for every system in every year. Computer Intelligence Corporation (CIC) provides information about the features of systems extant in 1991 and other important historical systems.[29] CIC's characteristics data cover roughly three-quarters of the most important mainframe and superminicomputer systems (used primarily in business applications) in 1981, or more than 90 percent of the installed base, which makes it more comprehensive than any other single data source. Table 8.1 shows that CIC characteristics data match an increasing fraction of the total number of models IDC surveyed. The sample size begins at 59 for 1968 and grows to 178 by 1981.

IDC provides a measure of the technical generation of a system. Dulberger (1989) warns that hedonic techniques may be mismeasuring the factors deciding prices when the data are taken from a cross section of systems in a market undergoing rapid technological "leap frogging" by successive new systems. Dulberger argues that this "disequilibrium" requires an explicit treatment in a hedonic framework. The simplest means of testing Dulberger's argument, as found in Berndt and Griliches (1993) and Oliner (1993), is to measure the time that has elapsed since the introduction of a system. This variable is labeled "techage." Systems that had more experience in the marketplace should have more software and other complementary system enhancements, which increased the system's quality for the user.

IDC's censuses categorize every system by size, with size ranging from two to seven. This measure is of limited usefulness for a regressor because it is categorical, not continuous, and is highly correlated with MIPS and memory. However, it will be useful for the simulations, because it is available for all systems, and therefore it provides a means for testing important differences between entry behavior on the highest and lowest ends of the computing-power spectrum.

Instruments (the z matrix) for each system are all of the characteristics data from the nearest lower and higher neighboring systems (for which there is characteristics data). These characteristics are typically exogenous, since they are designed by another firm. Yet they are also correlated with the characteristics of the neighboring system, so they make good instruments.[30]

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[28] Because minimum and maximum memory are highly correlated (between .6 and .7 in a year), only one could be used. Because there are many reasons to think that maximum memory is more relevant to buyers than minimum (Bresnahan and Greenstein 1992), maximum memory is used throughout the estimation.

[29] The measures of these variables come from CIC's 1991 Computer System Report, which has many virtues relative to the alternatives. The *Computerworld* data, which Professor Gordon kindly lent, begin in 1977. They cover too few systems up to 1981 to be useful. The Auerbach data, which Professor Michaels lent, cover the early part of the 1970s. Unfortunately, they also only cover a small number of years. While the Phister (1979) data cover a longer period, they generally only record the system characteristics for the most popular systems and not for the whole market. In fact, Phister's data cover only about 20–30 percent of the system models surveyed by IDC. CIC's data cover the same systems, plus many more.

[30] Thanks to Steve Berry and Frank Wolak for this suggestion.

Table 8.2 shows how the typical system in the sample changes over time. The average price of a system (deflated by a producer price index) and the average size of a system's installations included in the sample decline over most of the years of the sample. The typical system contains more memory (from 1,099 or 5,592 MB maximum memory on average) and performs more instructions per second (from 0.326 to 2.22). These statistics about MIPS and memory suggest that the product space was extended over the sample period, but they are insufficient for conclusions about the economic importance of the extension. The most dramatic changes in the average occur in the last three years of the sample upon the entry of some large supercomputers. Despite the addition of new systems to the sample, the average technical age grows (from 4.1 to 9.0); the inclusion of some very old systems in the sample of later years is to blame for this increase in the average.

Figure 8.2 provides an illustration of the diffusion of large systems and foreshadows results from the estimation. The figure shows a box plot of the distribution of MIPS in the computer systems used in each year.[31] The dark areas indicate the range between the first and third quartiles, while the white line shows the median. Every line above it represents a particular system until the maximum. While this is a coarse measure of computing capacity, the figure shows a gradual extension of the product space. It also shows a gradual buyer adoption of those extensions and a gradual shifting of revenues to systems with higher computing capacity. For example, the MIPS of the 95th percentile of 1968 is the median of the MIPS of systems in use by 1981. In addition, the product space between the maximum and the 95th percentile becomes progressively filled in over time with new products, even as these points vary. Yet many years must pass before the extensions of product space are widely adopted. The 95th percentile stays roughly the same between 1968 and 1973 and between 1974 and 1976, and it only begins to grow after 1977.

8.7 Results

This section presents estimates of the model and various tests of those estimates. The discussion also presents calculations of buyer's surplus and the rate of decline in the cost function. These estimates and calculations quantify the dramatic changes in the computer industry that took place over this period.

8.7.1 The Estimates

Table 8.3 presents estimates of the conjectural-variation model. With a few exceptions, most of the estimates of α and β are of the predicted sign and are significant. Systems with more computing power possess higher quality and

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[31] The figure shows only the MIPS ratings for the systems that were used in the estimation. While this is an incomplete sample of the systems in use, the coverage tends to be almost complete for the largest systems and the most popular systems. Hence, this provides a pretty accurate reflection of changes for the larger systems.

Table 8.2 **Sample Statistics**

Year	Mean	Standard Deviation	Variance	Minimum	Maximum	Sample Size
Maximum Memory (1,000 MB)						
1968	1.0993	1.7273	2.9836	0.0080	9.9200	53
1969	1.0962	1.7267	2.9816	0.0080	9.9200	60
1970	1.1426	1.7301	2.9933	0.0080	9.9200	64
1971	1.3489	1.8013	3.2445	0.0080	9.9200	67
1972	1.3197	1.5546	2.4168	0.0160	8.1920	77
1973	1.3984	1.6770	2.8123	0.0080	8.1920	88
1974	1.4783	1.8317	3.3550	0.0080	8.1920	96
1975	1.4520	1.7939	3.2182	0.0080	8.1920	101
1976	1.7331	2.3720	5.6264	0.0080	16.3840	113
1977	1.7934	2.5271	6.3861	0.0080	16.3840	122
1978	2.2391	3.9123	15.3063	0.0080	32.7680	136
1979	3.3615	6.1622	37.9726	0.0080	32.7680	138
1980	3.7290	6.4303	41.3483	0.0080	32.7680	155
1981	5.5925	11.7506	138.0776	0.0080	65.5360	166
MIPS						
1968	0.3264	0.2654	0.0704	0.1000	1.2000	53
1969	0.3983	0.6560	0.4303	0.1000	5.0000	60
1970	0.4203	0.6626	0.4391	0.1000	5.0000	64
1971	0.5060	0.7800	0.6084	0.1000	5.000	67
1972	0.5636	0.8637	0.7460	0.1000	5.0000	77
1973	0.5886	0.8647	0.7477	0.1000	5.0000	88
1974	0.5865	0.8571	0.7347	0.1000	5.0000	96
1975	0.5644	0.8413	0.7077	0.1000	5.0000	101
1976	0.6434	0.9436	0.8903	0.1000	5.2000	113
1977	0.6311	0.9163	0.8395	0.1000	5.2000	122
1978	0.6816	0.9593	0.9202	0.1000	5.2000	136
1979	0.9942	1.7482	3.0563	0.1000	15.0000	138
1980	1.0903	1.8502	3.4231	0.1000	15.0000	155
1981	2.2235	9.9076	98.1608	0.1000	99.0000	166
Monthly Rental Price (millions of 1982 $)						
1968	0.0801	0.0828	0.0069	0.0074	0.3844	53
1969	0.0840	0.1050	0.0110	0.0097	0.6434	60
1970	0.0939	0.1083	0.0117	0.0078	0.6210	64
1971	0.1134	0.1137	0.0129	0.0128	0.5815	67
1972	0.1104	0.1047	0.0110	0.0109	0.5103	77
1973	0.0987	0.0926	0.0086	0.0092	0.4302	88
1974	0.0859	0.0824	0.0068	0.0075	0.3963	96
1975	0.0767	0.0746	0.0056	0.0068	0.3583	101
1976	0.0694	0.0676	0.0046	0.0063	0.3336	113
1977	0.0720	0.0763	0.0058	0.0049	0.4143	122
1978	0.0687	0.0720	0.0052	0.0048	0.4089	136
1979	0.0731	0.0750	0.0056	0.0045	0.3731	138
1980	0.0638	0.0671	0.0045	0.0040	0.3575	155
1981	0.0584	0.0617	0.0038	0.0037	0.3379	166

Table 8.2 (continued)

Year	Mean	Standard Deviation	Variance	Minimum	Maximum	Sample Size
Number of Installations per System						
1968	362.3019	874.8564	765,373.6763	2.0000	4,550.0000	53
1969	357.8333	920.8783	848,016.8531	1.0000	6,000.0000	60
1970	394.2656	1,124.194	1,263,813.9442	3.0000	8,200.0000	64
1971	283.7015	908.7735	825,869.2429	1.0000	6,700.0000	67
1972	284.5325	798.1648	637,067.0154	1.0000	5,720.0000	77
1973	244.7841	603.0341	363,650.1482	1.0000	4,360.0000	88
1974	231.8021	489.3544	239,467.7604	1.0000	3,104.0000	96
1975	231.1980	485.6864	235,891.2604	2.0000	2,750.0000	101
1976	209.4956	457.7657	209,549.4129	2.0000	2,685.0000	113
1977	192.0984	399.0211	159,217.8580	1.0000	2,460.0000	122
1978	184.7353	354.0059	125,320.1516	1.0000	1,820.0000	136
1979	183.0507	352.5604	124,298.8368	1.0000	1,910.0000	138
1980	159.5032	306.8748	94,172.1477	1.0000	1,930.0000	155
1981	169.3735	391.1079	152,965.3991	1.0000	3,600.0000	166
Technical Age (years)						
1968	4.0758	1.9413	3.7686	0.3340	8.8340	53
1969	4.6989	2.1969	4.8262	1.0000	9.8340	60
1970	5.1931	2.5382	6.4426	0.9170	10.8340	64
1971	5.4792	2.9625	8.7765	0.2500	11.8340	67
1972	5.3781	3.2988	10.8823	0.8340	12.8340	77
1973	5.8166	3.4082	11.6161	0.4170	13.8340	88
1974	6.5785	3.7091	13.7573	1.1670	14.8340	96
1975	7.2281	3.8218	14.6060	1.1670	15.8340	101
1976	7.1648	4.2318	17.9084	1.3340	16.8340	113
1977	7.8173	4.2723	18.2525	1.1670	17.8340	122
1978	8.2595	4.6783	21.8868	1.1670	19.0000	136
1979	8.6930	5.0657	25.6615	1.0840	20.0000	138
1980	8.8090	5.4082	29.2483	1.0840	21.0000	155
1981	8.9833	5.7038	32.5337	1.1670	22.0000	166

have higher marginal cost. More memory contributes to the perceived quality of a product and to its increasing cost in all but the 1968 sample. Faster systems have higher quality and higher marginal costs in all of the estimates except the 1972, 1973, and 1980 samples, when the coefficients are not significant. Older systems usually possess higher quality and have higher marginal cost, but the coefficient is insignificant half the time on the supply side. Estimates for the size of the potential market are small, at 1 percent. For inapparent reasons, the model appears to fit badly in 1968, 1974, and 1980.

The variables measuring computing power are often quantitatively important on both the demand and the supply sides. These results are consistent with the basic assumption of this model, that computing power alone explains most of the cross-sectional variation in demand for computing. The varying

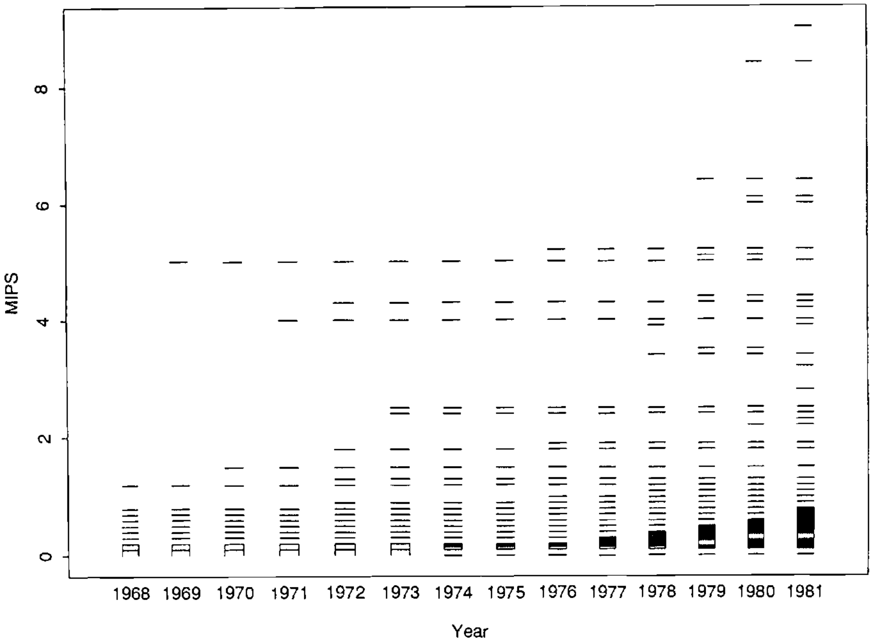

Fig. 8.2 Distribution of MIPS in use, 1968–1981

size of the technical-age variable does not support the view that disequilibrium pricing matters much for the model and data, which is also consistent with the methodological approach of this paper.

A curiosity of these first estimates is that coefficients on the supply side do not seem to show a large reduction in the costs of supplying characteristics over time. At most, there is a small (and erratic) downward shift in the costs of characteristics. This seems at odds with well-known declines in the costs of memory and processors. Later estimates showed that this pattern was an artifact of too much econometric freedom. A more constrained cost-function specification, more typical of the literature, will measure some anticipated decline below.

One other feature of these estimates has to do with the model's econometrics. The estimate of the implied quality of a system in one year has almost no econometric relationship to that estimate in another year. The model in each year requires that systems "price discriminate" between users with different willingness to pay for computing power, but it does not require similar quality estimates for a given system from year to year. Thus, nothing inherently ties down the estimates of the implied quality of a system from year to year and the estimates of surplus generated from those estimates of implied quality. Given this econometric freedom, it is remarkable that the coefficient estimates do tend to have the same sign and roughly the same order of magnitude from

Table 8.3 **Parameter Estimates: Conjectural-Variation Model**

	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
						Demand								
Constant	−2.54*	−2.41*	−2.56*	−1.46*	−2.02*	−0.59	−4.13*	−3.61*	−3.82*	−2.85*	−2.66*	−2.14*	−6.14*	−3.43*
Memory	−0.26	0.31*	0.25*	0.10*	0.33*	1.21	0.37*	0.41*	0.16*	0.05*	0.12*	0.07*	0.30	0.07*
MIPS	3.33*	0.08	0.21*	0.25*	−0.03	−0.94	0.18*	0.08	0.47*	0.58*	0.28*	0.18*	−0.20	0.08*
Age	0.04*	0.11*	0.13*	0.01	0.06*	−0.39	0.21*	0.11*	0.13*	0.05*	0.02	−0.03	0.32	0.04
						Supply								
Constant	−5.20*	−5.58*	−5.39*	−3.54*	−5.05*	−0.56	−6.73*	−5.96*	−5.39*	−5.30*	−4.26*	−3.90*	−9.02	−4.76*
Memory	−1.17*	0.75*	0.59*	0.50*	1.08*	3.36	0.59*	0.66*	0.27*	0.22*	0.27*	0.15*	0.46	0.11*
MIPS	12.4*	0.15	0.38*	0.35*	−0.37*	−2.90	0.33*	0.16	0.71*	0.97*	0.49*	0.38*	−0.32	0.13*
Tech-age	−0.15*	0.36*	0.34*	0.01	0.218*	−1.19	0.41*	0.24*	0.18*	0.13*	0.01	−0.01	0.50	0.05
exp (r)	0.015*													
exp (k)	90.04													
Weighted sum of squares	32.41													

*Significant at the 5 percent level.

year to year and roughly make sense. At the same time, the demand parameters are not close to constant across all years. These changes support the view that there are frequent changes to the basic relationship between the underlying valuation of computing capacity and the measurable features of computing capacity.

8.7.2 Testing the Model

The null hypothesis is that the conjecture parameter is zero, which is rejected. The value of the conjectural parameter rejects Bertrand pricing. The benefit to undercutting rivals is small, that is, price increases are closely matched. All specifications and experiments with this data, many not shown here, could not eliminate this result.

There are two fundamental reasons for this estimate. First, many products are priced close together, especially at the low end where many older systems are found.[32] The model must interpret these systems as close substitutes, especially when each system has such low market share. While this is probably the right inference for most systems with small market share, it underemphasizes the importance of systems that have significantly higher market share. Second, there is not enough flexibility in the marginal revenue equation to adapt to the wide dispersion of market shares in this data. The only free parameter is M, but M is constrained to be greater than the number of systems sold. While the model does attribute less-competitive elasticities to the high–market share systems, it may scale all the elasticity estimates incorrectly. M would have to become much smaller to generate elasticity estimates that are sensible for the high–market share systems. The conjectural-variation parameter provides more flexibility because it rescales the elasticities while retaining more-inelastic elasticities for systems with higher market share. Systems with large market share display elasticities consistent with large differences between marginal cost and price and high markups over marginal cost.[33]

This result suggests one of two things: First, if the model correctly describes product differentiation, then the firms behave quite differently from Bertrand pricing (i.e., they are much less aggressive). Second, using a hypothesis that is more plausible, the parameter may show that some factors outside the model—that is, factors other than the pricing and product differentiation modeled here—largely decide competition between vendors. This is plausible if vendors are competing by embodying unmeasured new features in each generation of their products. This possibility raises the same fundamental issues with

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[32] The difference between neighboring systems averages around 3 percent of the price of the lower-priced system, but grows for the higher-priced systems.

[33] Only a subset of the total number of systems available displays high markups over cost, which seems plausible. Inspection of the data reveals that these systems are almost always the systems with large market share and they almost always come from IBM. There is also a slight tendency for more-expensive systems to have larger markups in absolute value, but smaller markups as a percentage of price. This is because these systems are not as closely priced (in absolute value terms) to their neighbors as the lower-priced systems and they also have lower market share.

Table 8.4 Estimated Surplus (millions of 1982 $)

Year	Net Surplus per System	Net Expenditure Less Outside Good	Total Installed Base	Net Surplus per Dollar of Net Expenditure	Total Net Surplus
1968	.0701	649.53	25,641	2.76	1,796.84
1969	.0742	783.69	27,386	2.59	2,033.79
1970	.0694	892.01	29,283	2.28	2,033.82
1971	.1153	859.85	24,603	3.29	2,837.05
1972	.0938	923.13	26,920	2.73	2,525.84
1973	.0553	889.75	27,301	1.69	1,511.44
1974	.0334	864.14	27,787	1.07	929.47
1975	.0346	880.13	29,510	1.16	1,022.11
1976	.0287	866.50	31,583	1.04	909.08
1977	.0417	1,070.93	33,201	1.29	1,385.83
1978	.0388	1,163.21	36,209	1.20	1,407.28
1979	.0380	1,267.32	38,386	1.15	1,461.10
1980	.0187	1,337.63	43,798	0.61	820.33
1981	.0219	1,457.85	49,538	0.74	1,086.45

Notes: Net surplus measures the surplus generated net of the outside good. Net expenditure less outside good represents the expenditures on systems in the sample ($\Sigma P_j Q_j$) less the expenditure on the outside good ($\Sigma P_0 Q_j$).

which this paper began—that is, about the proper means for modeling product differentiation and behavior in this industry.

8.7.3 Buyer's Surplus

Table 8.4 summarizes the simulation of the consumer's surplus for each year for the conjectural-variation model. The estimates of net total surplus are large, roughly one to two billion dollars a month (these are net of the potential benefits of purchasing the outside good).[34] However, the estimates are also erratic, moving around by more than 50 percent from one period to the next. The average surplus per system, which controls for the changes in the number of systems in use in a year, makes more sense. These estimates also fluctuate, but less so than those that estimate the amount of total surplus. These estimates show an irregular but steady decline in the consumer's surplus per system after 1971. Table 8.4 also shows the net total surplus per net dollar of expenditure (net of potential expenditure on the outside good). This too shows a slow but steady decline after 1971.

There are several possible explanations for the decline in net surplus per system and net surplus per dollar. First, the model may increasingly fail to properly explain buyer exit from the mainframe market in the late 1970s. The availability of superminicomputers, which show up as devalued mainframe

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[34] Strictly speaking, this restriction makes these estimates of surplus incomparable with previous surplus estimates in this market (e.g., Bresnahan 1987b; Flamm 1987b; Brynjolfsson 1993).

computers in this model, could lie behind the trend. This solution is possible, but only partially successful. The rise in the net expenditure after 1977 is due to a large discrete change in the nominal price of the outside good (from $3,675 to $2,800) and to inflation in the late 1970s, which produces the decline in the surplus per expenditure after 1977. Yet no such simple explanation can account for trends between 1971 and 1976. The increase in the number of systems, which can explain the decline in net surplus per system, did not cause a corresponding increase in the total net surplus. The lack of increase in net surplus is still the mystery.

A second possibility, the most plausible one, is that the reduction of product differentiation to one dimension oversimplifies substitution possibilities. The model implausibly shows a crowded product space as new systems enter, as if all new entry occurs on intensive margins. In practice, many new systems may enter on extensive margins that this model cannot measure. This new entry generates gains in true, yet unmeasured, consumer's surplus. Therefore, the estimate in table 8.4 is too low, particularly in later years as systems get many new capabilities. This explanation suggest that, at best, these estimates can only do a good job of estimating surplus generated at the extensive margin (more computing capacity).

8.7.4 Importance of Entry on Extensive Margins

Table 8.5 displays estimates of entry on the only extensive margin in this model, more computing capacity. The table shows the amount of surplus attrib-

Table 8.5 **Percentage of Surplus Associated with Different Vintages and Sizes**

	Techage ≤ 4 Years Old		Techage ≤ 6 Years Old		Medium (size 5)		Large (size 6)		Very Large (size 7)	
Year	A	B	A	B	A	B	A	B	A	B
1968	.48	.37	.70	.62	.13	.06	.07	.03	.01	.01
1969	.08	.11	.73	.63	.15	.08	.08	.03	.02	.01
1970	.10	.14	.82	.71	.16	.08	.09	.04	.03	.01
1971	.06	.10	.16	.22	.19	.10	.11	.05	.03	.01
1972	.15	.15	.25	.29	.20	.11	.15	.07	.04	.02
1973	.29	.24	.36	.36	.23	.12	.17	.08	.05	.02
1974	.44	.32	.49	.41	.24	.13	.21	.09	.06	.02
1975	.27	.30	.53	.48	.25	.13	.19	.08	.06	.02
1976	.20	.29	.58	.53	.24	.13	.20	.08	.07	.02
1977	.10	.24	.44	.52	.21	.12	.20	.09	.08	.03
1978	.14	.23	.41	.50	.22	.13	.20	.09	.09	.03
1979	.23	.28	.35	.46	.22	.14	.21	.10	.11	.04
1980	.23	.15	.38	.34	.19	.11	.25	.10	.14	.04
1981	.31	.27	.49	.47	.17	.10	.23	.10	.14	.05

Notes: A: Surplus associated with types of systems as a percentage of total surplus. B: Percentage of installed base associated with the same type of system.

utable to systems in IDC's size-five, -six, and -seven categories, the top three categories in its ordinal ranking of system size. The percentage of surplus attributable to systems with high capacities grows over time. Roughly 21 percent of total surplus in 1968 is attributable to systems of sizes five, six, and seven, and only 8 percent to systems of sizes six and seven. This grows to as much as 54 percent for all, and 23 and 14 percent for sizes six and seven, respectively, in 1981. Much of the growth in size six comes before 1976, while growth occurs almost every year for size-seven systems. This reflects a general trend and is not an artifact of any arbitrary data definition of size by IDC.[35]

The table highlights two other factors about growth on the extensive margin. First, the fraction of the installed base of systems attributable to the high-capacity systems is small, never amounting to more than 10 percent of the total number of systems in 1968 and 25 percent in 1981. Yet this small fraction of systems accounts for a disproportionate amount of consumer's surplus—21 percent in 1968 and 54 percent in 1981. Part of this occurs because larger systems cost the customer more. Even though there are fewer of them, the expenditure per system is greater. Extending the product space a bit results in a huge increase of expenditure, though not nearly as many new units. This estimate supports the argument that growth on the extensive margin may have large influences on buyer's surplus.

However, the same estimates quantify a new aspect to extensive margin growth. Note how long it took for this market to register much growth on the extensive margin. Surplus in size seven undergoes steady but slow growth. Surplus in size six grows rapidly in the first half of the sample and slowly, but unevenly, in the second half. A close examination of the data illustrates why. The most popular size-six system, IBM 360/65, was first installed in late 1965. By 1968 users had installed over three hundred 360/65 models and over five hundred other more expensive systems. The IBM 370/155 then supplanted the 360/65 as the most popular system of size six in the early 1970s, but the diffusion took several years to reach its peak. By the late 1970s, however, no single system dominated the large-system-size category any longer. There was only gradual change on the extensive margin in the mid- to late 1970s as new systems only slowly became widely used. The slow but steady entry of many different new systems accounts for most of the growth in the late 1970s.

Table 8.5 also presents estimates of the percentage of surplus in each year attributable to systems of different vintages, principally those less than or equal to four and six years old. This partially addresses the concern that new products not only are cheaper, but embody new unmeasured features not reflected in the price. First, as expected, young vintages tend to generate the most surplus, averaging 22–47 percent of surplus, depending on the measure. This

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35. For example, IDC's censuses show a perceptible decline in the entry of size-two systems after 1976 (Greenstein 1994). Yet this bias does not explain the time trend in table 8.5 because most size-two systems were not included in this sample as a result of the adoption of a consistent definition for the outside good.

result, combined with the inability of technical age to predict system demand, suggests that buyers purchase systems for more than just capacity, but this quality is not measurable in a simple manner. Second, the importance of young vintages differs dramatically from year to year. A few specific vintages influence surplus estimates. The technical vintage introduced in 1965–66 dominates the surplus calculations until the mid-1970s, which unquestionably reflects the popularity of the IBM system 360. The next major wave of surplus is associated with IBM system 370 (mostly from 1971 and 1973). These two vintage effects do not work themselves out until virtually the end of the sample, when the entry of many new systems begins to influence the surplus simulations.

No other family of systems generates so much surplus as the systems 360 and 370 because no other family of systems has such a large market share. While this qualitative result is not surprising (see Greenstein 1994), it raises important issues. First, it suggests that estimates of the benefits from technical change in the early years of computing are determined by estimates of the benefits associated with the technical improvements in a few of the dominant systems of that era. Only in the later years are the benefits spread across more models. Second, it highlights the importance of properly measuring the benefits associated with the system 360/370. In any quantity-weighted measurement exercise, such as the above, small changes in estimates of the benefits associated with the system 360/370 lead to large changes in estimates of the benefits to society from technical changes in computing. This observation adds importance to the debate about the (measured) economic benefits associated with the system 370 (e.g., see Dulberger 1989; Gordon 1989; and Triplett 1989) and about whether most of the benefits from technical change accrued to buyers. Finally, these results again raise the unresolved question about the proper method for weighting a popular system relative to less commercially successful systems in a hedonic regression.

Table 8.6 puts the pattern of entry into final perspective. It computes the counterfactual surplus generated if all new systems were absent (those less than four and six years old). It displays this counterfactual surplus as a fraction of buyer's surplus measured with all the systems. This is in the spirit of welfare calculations that keep the demand characteristics fixed but alter the choices available to buyers. Removing young systems simulates demand in the absence of any technical change.[36] Not surprisingly, surplus declines without new systems. However, in any given year it does not decline by more than a few percentage points. The largest declines are associated with the counterfactual elimination of the system 360 in the early years of the sample. In the mid-

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[36] It seems less plausible to estimate the counterfactual surplus in the absence of a system of a particular size. In that counterfactual world, there would be a large supplier response in short-run pricing behavior and long-run design behavior. Simulating that counterfactual behavior does not make any point that cannot already be made with the results in table 8.6.

Table 8.6 **Size of Counterfactual Surplus as a Percentage of Observed Surplus**

Year	Techage ≤ 4 Years Old Removed	Techage ≤ 6 Years Old Removed
1968	.961	.938
1969	.997	.919
1970	.994	.875
1971	.991	.990
1972	.994	.982
1973	.986	.979
1974	.973	.970
1975	.977	.963
1976	.982	.958
1977	.986	.965
1978	.985	.965
1979	.982	.972
1980	.990	.980
1981	.984	.975

1970s the decline is less than 1 percent and less than 3 percent by the late 1970s, especially for young systems.

Table 8.6 displays a well-known characteristic of counterfactual welfare measures of technical change: a new technology is only as good as the alternatives to it are bad. Even if no new systems were invented, buyers would continue to use old technology. In this model, old systems are very close substitutes, and switching between substitutes is assumed to be costless. The product space is "crowded" as a result, so that the absence of a new technology sends buyers to a worse, but lower-priced, system. Since entry on the intensive margins can only generate large gains when the product space is not crowded, the biggest gains to such entry in this model are recorded early in the sample, when the industry is still young. Since this crowding is probably an artifact of not measuring all the dimensions that buyers value, and table 8.5 shows that a substantial number of buyers continue to purchase young systems, table 8.6 represents a (potentially severe) underestimate of the true surplus losses.

Table 8.6 echoes the observation that innovation takes a long time to achieve its full effect (only here it is about the entry of new systems). Though the net benefit from new systems is small in any given year, the cumulative effect over many years is quite large. That is, if all technical change had ceased in 1968, by 1981 the cumulative losses in each year would have been enormous. However, not to belabor the point, the long-run estimate of loss is surely an underestimate. Much evidence suggests that important product characteristics are not being measured here. The amount of mismeasurement must increase as the time periods in comparison become further apart.

Tables 8.5 and 8.6 embody both the strengths and weaknesses of the approach taken in this paper. On the one hand, standard hedonic methods could not lead to these tables or to the conclusions reached from them. Table 8.6 quantifies the benefits from new technology in use, while hedonic price methods stop at estimating improvements in what is available. Though this paper's conclusions require structural assumptions about the nature of demand, this is par for the course in using data on both quantities and prices. Any other structural model that incorporates more dimensions will necessarily show the same effects highlighted in this paper and possibly more. On the downside, tables 8.5 and 8.6 are only as good as the structural assumptions that generated them. Parts of this paper (and other analyses of this market, e.g., Bresnahan and Greenstein 1992) suggest that product differentiation is incompletely modeled here and potentially correlated with age. Entry probably also occurred on more extensive margins than are modeled. If that is so, tables 8.5 and 8.6 provide a lower bound on the welfare losses from the absence of innovation.

8.7.5 Cost Function Decline

Table 8.7 estimates cost functions on exactly the same data as were used in table 8.3. The two equations use something akin to standard hedonic specifications but supplement them with a market-power correction, as found in a vertical model with conjectural variations. The first specification takes the form

$$\ln(P_j) = \Gamma Q_j/[P_j Mg(P,Q,M)] + x_j\alpha + e_j. \tag{7}$$

The next specification is similar, but specifies a different Γ over time. The market size, M, is assumed to be about 1 percent larger than the observed market, taken from the previous conjectural-variation estimates in table 8.3.[37] All the data are pooled such that α has one coefficient for MIPS, memory, and age, but different year-dummy coefficients, which captures the change in the level of the cost function of firms.[38] This assumes that all firms draw from the same cost function in a given year. Rather than explicitly model the demand size, which is of little interest here, the estimates employ a reduced form for demand. Demand is a function of the same set of regressors and instruments as used previously, plus time dummies. This treats MIPS, memory, age, and market power as endogenous and the time dummies as exogenous.

The cost function estimates have the following three features: First, coefficients for memory, MIPS, and age all have the correct sign. Second, none of

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[37] The above results suggest that little is lost by estimating a conjectural-variation model as if M is known (even when it is not). In any event, in a conjectural-variation model, the conjectural parameter would scale any estimate, effectively acting in the opposite direction of any estimate of the market size. Hence, it is must easier, and no less insightful, to simply assume a given size of a market, compute the implied product elasticities, and then estimate a conjecture parameter to scale the elasticity estimates properly.

[38] Though the dummy coefficients are unbiased estimates, the index will not be. It is a nonlinear function of an unbiased estimate. To correct for this bias, the estimated standard errors use an approximation suggested by Triplett (1989). This involves adding one-half of the standard error to the coefficient before computing the index.

Table 8.7 Cost-Function Estimates

Sample Statistics

Variable	Mean	Standard Deviation	Variance	Minimum	Maximum
Year	1975.8816	3.8561	14.8696	1968	1981
Memory	2.4305	5.4442	29.6394	0.0080	65.5360
MIPS	0.8553	3.5653	12.7110	0.1000	99.0000
Techage	7.2617	4.5623	20.8143	0.2500	22.0000
ln(price)	−3.0553	1.0447	1.0913	−5.6011	−0.4409

Correlation of Variables

Variable	Memory	MIPS	Age
MIPS	0.24271562		
Techage	−0.25643255	−0.12986814	
ln(price)	0.26571416	0.22847909	−0.14177210

Specification 1

Valid cases = 1,436
$R^2 = 0.218$
Residual SS = 4,315.12
Dependent variable = ln(price)
$\bar{R}^2 = 0.209$
Standard error of estimates = 1.744

Variable	Estimate	Standard Error	Real Cost Index
Memory	0.276	0.0471**	
MIPS	0.166	0.0763*	
Techage	0.155	0.0771*	
Γ(CV parameter)	−655.9	128.8**	
1968	−3.602	0.41**	100.0
1969	−3.678	0.45**	94.6
1970	−3.435	0.49**	123.1
1971	−3.457	0.50**	121.6
1972	−3.426	0.49**	124.2
1973	−3.771	0.51**	88.8
1974	−4.013	0.57**	71.8
1975	−4.425	0.61**	48.5
1976	−4.693	0.60**	37.1
1977	−4.658	0.65**	39.2
1978	−5.061	0.69**	26.7
1979	−5.448	0.74**	18.4
1980	−5.806	0.75**	13.1
1981	−6.615	0.81**	6.0

(*continued*)

Table 8.7 (continued)

Specification 2
Valid cases = 1,436
$R^2 = 0.193$
Residual SS = 6,367.5
Dependent variable = ln(price)
$\bar{R}^2 = 0.182$
Standard error of estimates = 2.120

Variable	Estimate	Standard Error	Real Cost Index
Memory	0.234	0.0707**	
MIPS	0.127	0.106	
Techage	0.066	0.120	
Γ (1968–69)	−132.7	252.3	
Γ (1970–76)	−983.5	204.6**	
Γ (1977–81)	−1,470.3	603.0*	
1968	−3.479	0.52**	100.0
1969	−3.511	0.56**	98.8
1970	−2.586	0.67**	261.9
1971	−2.668	0.68**	243.7
1972	−2.635	0.67**	249.4
1973	−3.000	0.69**	174.9
1974	−3.141	0.77**	158.1
1975	−3.598	0.81**	102.1
1976	−3.897	0.80**	75.7
1977	−3.470	0.99**	127.0
1978	−4.023	0.96**	72.3
1979	−4.313	1.04**	56.3
1980	−4.751	1.02**	36.0
1981	−5.419	1.12**	19.4

*t = value exceeds 1.96.
**t = value exceeds 2.56.

the estimates shows a monotonically declining rate of technical change. The most problematic of all the estimates are those for 1968 through 1970, which may be due to changes in IDC's sampling frame in those years. This problem does not seem to be a manifestation of the movement from the IBM 360 to the IBM 370, which was first introduced in 1971. Third, all the estimates measure rapid rates of technical change over the long run. The first equation, which estimates only one conjecture parameter for the entire sample, finds a decline in the cost function of 20.0 percent over fourteen years and 30.3 percent from 1971 to 1981. The second equation, which estimates a different conjecture parameter for each of the three IDC sampling periods, estimates declines of 11.7 percent over fourteen years and 25.5 percent from 1971 to 1981.[39] The

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[39] Interacting a time trend with the conjecture parameter did not result in qualitatively different conclusions. The first equation is presented because it is easier to read and interpret.

differences in the estimates suggest that functional form influences the precise estimate of change in market power and the change in the cost function. In both cases, decreases in the prices to consumers were due partly to changes in market power and partly to declines in the cost function.[40]

8.8 Conclusion

This paper measures the economic benefits that accrued to buyers from technical innovation in mainframe computers. The thesis is that many innovations that created economic value in this period are associated with extensions in computing capabilities. Answers to the questions raised in the introduction provide a suitable summary of this analysis.

What valuable innovations in this period are associated with extensions of capabilities? It was argued that technical change in the computing market involved much more than rapid declines in the price of existing capabilities. While price declines enabled many of the events that took place, important episodes of value creation were associated with specific inventions that extended buyer capabilities into new areas—for example, the invention of reliable real-time database querying and the invention of interruption-free multiuser computing. Value creation was not associated solely with the decline in costs of the delivery of these services.

Do buyers adopt products that embody extensions of capabilities? The economic history and the econometric results show that adoption decisions were not solely the result of buyers taking advantage of lower prices for existing capabilities. The data and estimates show that many buyers purchased larger computing capacity embodied in products that came into existence in the 1970s.

How does a measurement framework represent that action? This study argued that some fraction of the new capabilities associated with new systems is not measurable but is complementary with increases in computing capacity. Therefore, a model of the supply and demand for products with different computing capacity will capture some demand for new capabilities. Such a model has several interesting features: (1) buyers slowly adopt higher-capacity systems, suggesting that greater attention needs to be paid to the diffusion of new technology in this market (Greenstein 1994); (2) decreases in prices to consumers were due partly to changes in market power and partly to declines in cost. All the estimates measure rapid rates of decline in the costs of providing computer capacity over the long run.

[40] Finally, it is not correct to infer that market power increased over time just because Γ increased. Instead, one must examine changes in the distribution of product-specific elasticities. Close examination of these elasticities, not shown here, reveals a more competitive market over time—in the sense that the median product-specific elasticity is more elastic, as is every other order statistic of the elasticity. This is not surprising in this model since the product space becomes increasingly crowded over time.

Are most extensions only embodied in capacity or other features of the products? Competition in computing is partially represented by extensions in computing capacity and by the technological age of systems, but not entirely. The conjectural-variation estimates and the demand-parameter estimates suggest that there was not a stable relationship over time between measurable features of products and revealed buyer choice. This is not surprising because of the well-known changing value of outside goods. It is also not surprising because of the likely changing valuation of computing capacity that resulted from innovation of complementary components. Therefore, constant-quality indexes of price decline potentially omit the factors that influence changes to economic welfare for many buyers.

In sum, much significant innovation in this industry was associated with extending capabilities to new levels. This is not an argument that price decreases were unimportant to buyers, only that price decreases do not tell the whole story about the welfare improvements realized by buyers—perhaps they even tell a deceptive story. There are many implications from this conclusion for understanding competition and value creation in this industry (e.g., see Bresnahan and Greenstein 1992). This study focuses on whether constant-quality price indexes provide good information about welfare benefits from technological change. They do for the buyers who continue to buy products with similar sets of characteristics, but not necessarily for the buyers who take advantage of the availability of characteristics that did not previously exist. Many buyers fall into this latter camp. It is time that these observations about extension of capabilities became a central part of the discussion about the creation of economic benefits from technological change in computing.

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Comment Erik Brynjolfsson

The proliferation of new goods in the economy over the past several decades has been indirectly enabled by a ten-thousand-fold improvement in the performance of computer technology. Computers give companies the capability to manage the complexity of developing, producing, marketing, and servicing ever more products. They are new goods which enable even more new goods. Of course, in addition to this indirect effect, the unprecedented improvement in the underlying technology has had a direct impact on the computer industry itself, where new generations of products arrive at a pace measured in months.

Shane Greenstein has undertaken the important job of estimating the contribution that new mainframes made to welfare in the 1970s, when they were the dominant class of computers. This is not an easy task. The evolution of this paper through three revisions and three presentations reflects substantial effort.

This paper reflects state-of-the-art research, and the basic thesis, that growth on the extensive margin is a major source of surplus in the mainframe computing market, is sensible. Nonetheless, one of the lessons I take from this paper is that the methods applied must be used with great care. We do not yet have a "silver bullet" for evaluating the value of new goods. This point can be best illustrated by stepping back and putting the reported results in perspective. Accordingly, after summarizing some of the main contributions of Greenstein's paper, I will contrast them to the inferences that could be made from a somewhat simpler look at the data.

This paper has a number of strengths. First, Greenstein has chosen a critically important topic. Computers are an increasingly large contributor to economic welfare, and the main hypothesis of the paper, that extending the capabilities of computers is important, is clearly on target.

Second, the paper makes use of a very promising, underexploited data set which provides broad coverage of the rental prices of mainframes and their installed base. Identifying and working with this kind of detailed data is not easy and needs to be commended whenever it is done. Often, a great deal can be learned by even a first pass through such data. Indeed, the simple plot in figure 8.2 makes the key point that mainframe capabilities have grown over time nearly as effectively as the tables derived from more detailed calculations.

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Third, this paper represents the first use outside of the automobile industry of some of the tools developed by Bresnahan (1987) and Berry (1994). The mainframe market seems as though it might be fertile ground for these tools insofar as vertical differentiation is an important characteristic of this market. There is a large spread in the power of systems, whether measured by the speed of the CPU, the amount of random access memory, or the storage capacity, and that power is highly correlated with the price of the systems. Of course, horizontal differentiation is also important in this industry; how much this will affect the results is difficult to know in advance.

Fourth, Greenstein demonstrates some technical innovations which overcome a number of difficulties with the data and help account for some important features of the mainframe market. For example, by including a conjectural-variation parameter to account for competitive response to price changes, Greenstein's model is an improvement over the hedonic approach which typically assumes a constant markup. As a result, he is able to present evidence that some of the decline in prices in mainframes may have been due either to an erosion of IBM's monopoly power or to the diminution of network externalities associated with the value of the IBM standard. Another technical innovation is adapting the Bresnahan-Berry model to a data set with some missing observations. Greenstein also had to do some work to derive reasonable-looking cost functions. By judiciously adding some additional constraints to the model, cost declines became evident on an order of magnitude that is comparable to that found in hedonic models.

With all these strengths, the ingredients are in place for some important results. The reported results can be grouped into three sets. The main finding was that entry on the extensive margin was economically significant. A careful reading of the last column of table 8.4 indicates that mainframes generated over one thousand million (i.e., one billion) dollars of surplus per *month* in 1981, or about $13 billion per year. Table 8.5 shows that the larger mainframes accounted for an increasing share of this amount: the surplus due to class seven mainframes, IDC's largest category, rose from 1 to 14 percent.

Second, while Greenstein finds evidence that the extensive margin was growing in importance, his results also imply that neither consumers nor producers benefited much overall. Table 8.4 suggests that the total surplus in this market has declined over time, despite a rapid increase in spending and the installed base. This finding is particularly striking given the increases in product quality which we know to have occurred in this industry and which are confirmed in table 8.7. Interestingly, note 40 reports that the decline in surplus cannot be attributed to more-monopolistic pricing. Indeed, producers also lost out: competition increased in this market as measured by median product elasticity.[1]

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[1] For IBM, by far the biggest mainframe producer, the worst was yet to come. See Bresnahan and Greenstein (1994).

The final set of results suggests that diffusion was slow and the new systems added little to surplus. Amazingly, the model predicts that if all systems less than four years old were removed from the market in 1981, surplus would have been reduced only by 1.6 percent!

While each of these results was derived by the careful application of state-of-the-art theory to the best available data, they are subject to important qualifications. In particular, several of these results call for closer scrutiny because they are not consistent with some of the conventional wisdom regarding the market for mainframe computers. For example, the welfare estimates, while large, may still be too low; the reported decline in surplus over time is suspect; and the small welfare contribution of new goods (less than four years old) is almost certainly incorrect, or at least misleading, given the blazing technological advances in this industry. While it is always interesting to see long-held beliefs challenged, in this match, I think the weight of the evidence will still be found to be on the side of the conventional wisdom.

Let's begin by looking more closely at the estimates of total surplus. It is useful to compare Greenstein's analysis with a simpler benchmark estimate based on the demand curve implied by the decline in the price of computer power and the concurrent increase in the quantity of computer power purchased. This approach will make some different assumptions which highlight the role of price declines in creating welfare benefits (as opposed to extensions in the product space).

To simplify the analysis, suppose that the computer power that can be purchased for a dollar has similar welfare characteristics, regardless of where that dollar is spent. In other words, a key departure from Greenstein's approach is that we now make the assumption that the ratio of surplus to spending is unaffected by the mix of big systems and smaller systems in a given year.[2] We shall see below that this assumption does not appear to be far from the truth. The resulting welfare estimates will not be strictly comparable to Greenstein's but can be used to put his estimates in perspective.[3]

Over the past several years, one well-documented feature in the computing sector has been dramatic decline in the cost of computing: on the order of 20 percent per year (e.g., see Gordon 1993). In theory, price declines can be caused by shifts in either supply or demand, but there can be little doubt that this magnitude of decline must be due almost entirely to one thing: technical change in the production function. In fact, technical change in the computer industry is relatively well-understood and is remarkably predictable (Grove 1990). A rather fortuitous combination of physics, geometry, and materials science has enabled microchip performance to double every eighteen months for the past three decades.

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[2] This is not the same as the stronger assumptions that surplus per computer or surplus per unit of computer power are constant.

[3] The results will be more comparable to those of Bresnahan (1986) and Brynjolfsson (1993, 1996), who undertake similar, if more detailed, exercises.

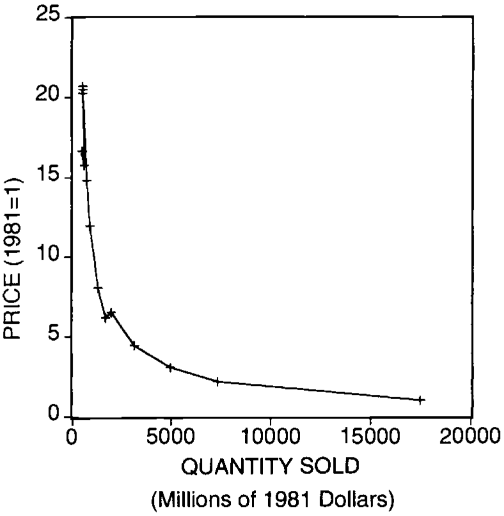

Fig. 8C.1 Mainframe price versus quantity, 1968–1981

Given this knowledge of the underlying dynamics of price change, there is less need for the traditional agnosticism of economists regarding the source of the price changes derived from hedonic estimates (e.g., Griliches 1990, 189). Clearly, the steady decline in the price of computer power is due mainly to a shift of the supply curve, and this is consistent with Greenstein's cost function estimates for the mainframe market.

This knowledge enables us to identify a benchmark demand curve, as suggested by figures 8C.1 and 8C.2, using the values for price and quantity based on Greenstein's tables 8.7 and 8.4, respectively. Indeed, demand appears to be well fit by the traditional log-linear specification:

$$q = e^{\gamma} p^{\alpha} y^{\delta},$$

where q is quantity (based on Greenstein's table 8.4), p is price (based on Greenstein's table 8.7), y is income (from real gross domestic product reported by the Council of Economic Advisers 1992) and γ, α, and δ are parameters. The parameter estimates, based on a simple regression, are reported in table 8C.1.

Given such an estimate of demand it is easy to generate a straightforward estimate of exact consumer's surplus (Hausman 1981).[4] This back-of-the-envelope calculation suggests that the increase in consumer's surplus attribut-

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[4] The increase in exact consumer's surplus from a price change from p_0 to p_1 is given by

$$\{(1-\delta)[e^{\gamma}(p_1^{1+\alpha} - p_0^{1+\alpha})/(1 + \alpha)] + y(1 - \delta)\}/(1 - \delta - y).$$

In principle, this approach should capture some of the benefits of new goods through the increase in quantity sold, but it will be an underestimate if these new goods contribute disproportionately to welfare.

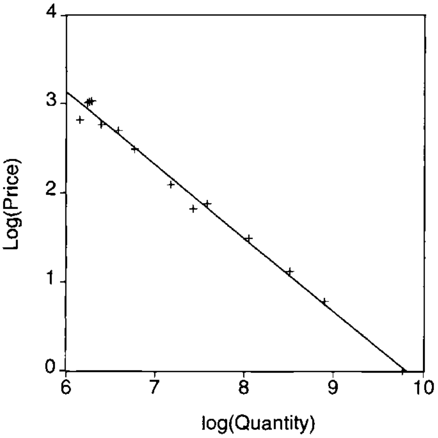

Fig. 8C.2 Log (price) versus log (quantity), with regression line

Table 8C.1 **Regression Estimates for the Demand for Mainframe Computers as a Function of Price**

Dependent variable = LQUANT81
Sample range = 1968–1981
$N = 14$
$R^2 = 0.994$
Adjusted $R^2 = 0.993$
Standard error of regression = 0.0963
F-statistic = 912
Mean of dependent = 7.29
Standard deviation of dependent = 1.14
Sum of squared residuals = 0.102

Variable	Coefficient	Standard Error	t-statistic	2-Tail Significance
C	−11.9	8.63	−1.38	0.194
LPRICE81	−1.05	0.0677	−15.6	0.000
LGDP	1.44	0.573	2.52	0.029

able to the price decline in mainframe computer power between 1968 and 1981 was about $43.9 billion in 1981.[5] This is likely to be an underestimate of surplus, since, inter alia, some allowance should be made for the fact that, due to diffusion, the demand curve probably shifted outward somewhat over this period, beyond the increase in GNP.

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[5] Log-linear demand is also consistent with the application of the index number method used by Bresnahan (1986), which gives a slightly higher estimate of about $49.2 billion. Either figure is consistent with the finding in Brynjolfsson (1993) that consumer's surplus in the overall computer market amounts to three to four times expenditures. Another interesting point of reference is IBM's 1981 net income of $4.4 billion and 60.2 percent gross margins.

What can we learn from such a benchmark estimate? In comparison, Greenstein estimates that surplus from advances in the extensive margin of computing was $13 billion for 1981. This benchmark exercise supports his contention that the extensive margin was an important component of mainframes' contributions to economic welfare, although perhaps less important than I would previously have guessed.[6] Because Greenstein's surplus estimates are based on a changing definition of the "outside good" over time, it is difficult to interpret the figures much further.

However, as Greenstein notes, his method should lend itself more fruitfully to relative comparisons, such as the proportion of welfare generated by computers of various sizes. In particular, he reports that 14 percent of surplus is generated by the 5 percent of units in the highest size class in 1981. This appears to suggest that large systems contribute disproportionately to welfare. However, this statistic must be interpreted carefully. Since large units are much costlier, a more relevant comparison would be the amount of welfare generated versus the dollars spent on these units. Greenstein has stated that the largest computers also account for about 14 percent of spending in 1981, so ironically, this suggests that, in terms of surplus, perhaps large systems *can* be modeled as "clumps" of small systems. If this is the case generally, then the benchmark surplus estimates derived above may not be far from the truth.

It is important to note, however, that without Greenstein's analysis, the assumption that welfare was proportional to spending for large systems could not have been tested. It is certainly not true that mainframes are technologically equal to collections of smaller machines in cost per unit of computer power. Since we know that mainframe users pay a higher unit price for their computer power, they must also be getting greater benefits. These benefits need not necessarily scale up proportionately, since, because of indivisibilities in many computational tasks, one cannot fully arbitrage processing power on PCs for processing on mainframes, client-server architectures notwithstanding.

If the amount of surplus attributable to large systems seems broadly consistent with what we know about the mainframe market, the reported decline in measured surplus over time is more difficult to explain, especially given the rising expenditures on mainframes and their growing capabilities. One possibility is that because the measured benefit is net of outside good, this result could be a function of the powerful minicomputers encroaching on the mainframe market. It is true that mainframe software was ported to many minicomputers in the 1970s and the data set is missing many of these machines, particularly in DEC's VAX line. However, total expenditure on mainframes continued

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[6] My spoken comments on the two previous versions of his paper were much less supportive of his main result. Based on a similar benchmark analysis, I then argued that his estimates were probably off by at least an order of magnitude. However, in the latest version of the paper, Greenstein's original estimates of $1–2 billion *per year* have been updated to be $1–2 billion *per month.* Since his original calculations were internally consistent, this fact might never have been noticed without the "reality check" provided by the benchmark method.

to rise over this period, leading Greenstein to discount the role of increasing capabilities of the "outside good" as an explanation.

Nonetheless, a slightly more complex story may be viable. Begin by noting that the Greenstein model measures the *marginal* surplus associated with the last bit of computing power, not the average or total surplus. As the portion of the vertically differentiated product space occupied by mainframes moved "up," it is possible that the marginal surplus from mainframe computing declined, although the total benefits of computers might have been increasing. A related story could be told in which increasingly less-valuable niches in the mainframe market were gradually filled over time, leading to lower marginal benefit but increasing total surplus.[7]

However, I agree with Greenstein that the most compelling explanation for the decline in measured surplus is the growing importance of horizontal differentiation. The rise of the horizontal differential suggests that there are many extensive margins to the computing market and that a one-dimensional vertical-differentiation model is too simple in this application. In fact, much of the value to consumers probably came from the new uses of *low end* computers that were enabled by complementary innovations in software and other products. In the 1970s, this meant dedicated word-processing systems and special-purpose minicomputer packages. In the 1980s, personal computers were made valuable by dozens of new applications and markets. In the 1990s, it appears that game machines and "smart" cable-television boxes may create some of the biggest fortunes and consumer benefits.[8]

As suggested by figure 8C.3, marketing experts in the computer industry, such as former Apple CEO John Sculley, do not tend to think of the product space as being most meaningfully described by a single vertical dimension. While there are numerous extensive margins in "Sculley space," mainframes don't appear to be on any of them. To put it another way, given the general-purpose nature of computer power, it seems unlikely that vendors and users would soon exhaust its potential for new applications and new markets even if there were *no* further advances in the power delivered at the high end of the market.

Because the product space may be getting more crowded in the horizontal dimension as different products address different markets but do so with comparable amounts of computing power, the vertical-differentiation model may

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[7] If the definition of the outside good had remained fixed in absolute terms, instead of changing each year, the increase in total surplus would have been more evident. This is apparent in figure 8.2.

[8] The term "low end" is only relative: Nintendo's 64 video game player, scheduled for release in early 1996 at a price of $300, is aimed at providing three-dimensional "virtual reality" gaming for young teenage boys. To address this new application, the machine uses a 64-bit microprocessor running at 100 Megahertz which delivers 125 MIPS of raw computing power. In contrast, the most powerful mainframe available in 1980 (in Greenstein's sample), delivered 15 MIPS for a rental price of about $350,000 a month. (Of course, MIPS is only one measure of a computer's power.)

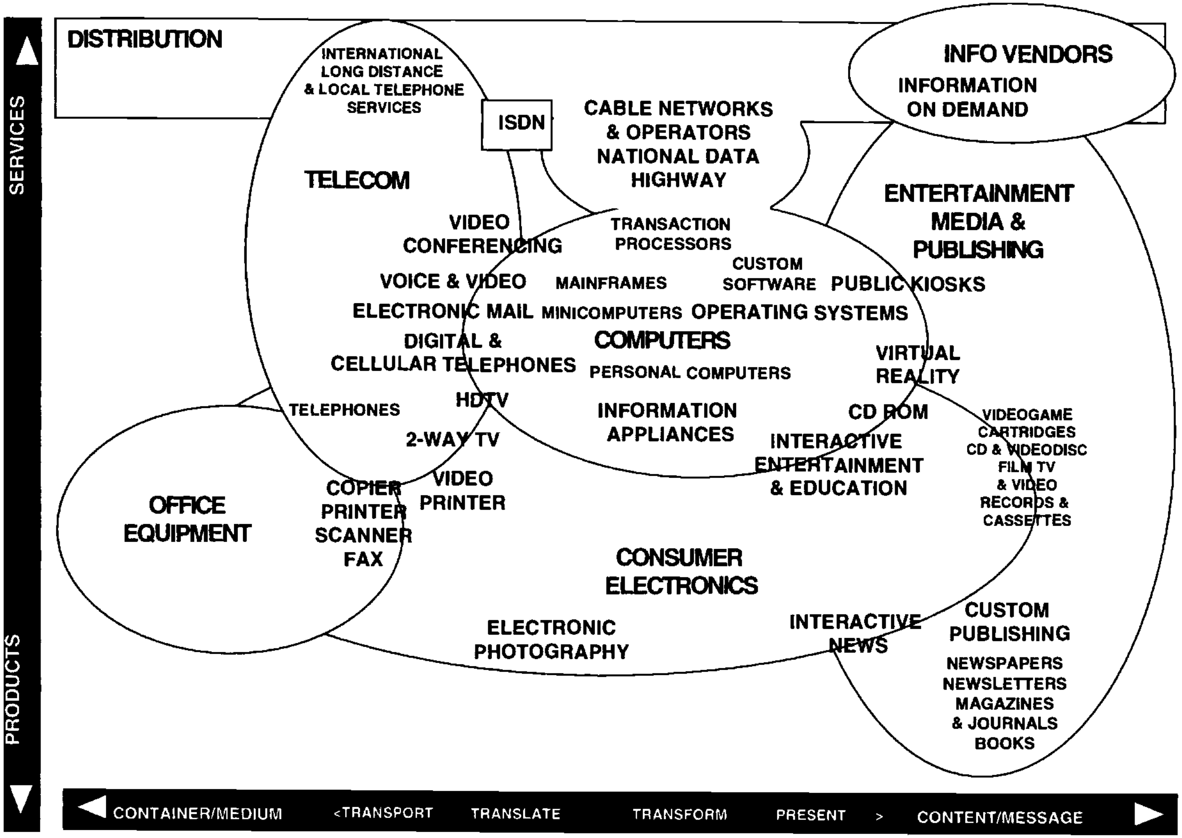

Fig. 8C.3 Merger mania: the information industry in 2001

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not be valid even for relative comparisons over time. For instance, Greenstein's finding that the market appears to be growing more competitive may simply be an artifact of neighbors in the vertical dimension looking like substitutes even when they are not.

Growing horizontal differentiation can also account for the counterintuitive finding that new systems (less than four years old) added so little to surplus in any given year. A vertical-differentiation model will underestimate the contribution of new goods when it assumes that a new Wang word-processing system merely substitutes for an old IBM transaction-processing system with comparable processing power. This makes it look like eliminating Wang would not have affected welfare much.

In comparison, the benchmark welfare contribution of the price declines embodied in new technologies are apparently much larger. For instance, a 20 percent decline in prices between 1980 and 1981 would have increased exact consumer welfare by $3 billion, or 7.5 percent, using the demand-curve estimates presented above.

What can we learn from this work? Certainly Greenstein has addressed an important problem and valuable insights spring from his data and analyses. Perhaps most importantly, Greenstein's paper underscores both the strengths and the weaknesses of the vertical-differentiation models and will set future work on a firmer foundation. While the interpretation of the absolute value of the surplus estimates derived is difficult, it appears that relative comparisons can be more meaningful. For instance, one of Greenstein's most important contributions is in establishing that the welfare contributions of very large classes of mainframes are significant, although not necessarily disproportionate to expenditures on them. On the other hand, the counterfactual estimates of the welfare losses from eliminating machines of recent vintages are almost certainly too low. This highlights the fact that a vertical-differentiation model will underestimate the surplus contribution of new goods when horizontal differentiation is important. Unfortunately, it seems as though this will become an increasingly important weakness as more new goods appear in the economy which cannot be differentiated solely by a one-dimensional quality metric.

The somewhat humbling message is that our tools are still fairly blunt. Estimating the value of new goods may still be an area in which economics is a one-digit science. Accordingly, whenever possible we will need to use multiple methods to triangulate on an answer. My own bias is that a simple pass through new detailed data may often be one of the most informative approaches. For example, Greenstein's figure 8.2 told most of the story of his paper and struck me as a more reliable basis for practical inference than some of the more sophisticated analytical results he also presented. A related point is that reasonableness checks based on knowledge of the specific domain being analyzed can tell us whether our estimates are at least in the right order of magnitude. Insights flow not only from models to our knowledge of the world, but also in the reverse direction.

The economy is evolving in directions that make this type of analysis increasingly critical and I certainly expect that it will be successfully applied again in future empirical work. For most goods, looking only at price declines may miss most of the welfare benefits. Perhaps the computer market is one place where the simple price-decline approach does not do too much injustice. More likely, a focus solely on either price declines or vertical differentiation will miss important features of the market: future work will need to look at margins in other dimensions. In any case, Greenstein's paper unquestionably advances the extensive margin of economic research on the value of new goods.

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