The Intangible Costs and Benefits of Computer Investments:
Evidence from the Financial Markets

Erik Brynjolfsson
MIT Sloan School
erikb@mit.edu

Shinkyu Yang
MIT Sloan School
skyang@mit.edu

May, 1997; Revised December, 1999

ABSTRACT

We show how the financial market valuation of firms can be used to estimate the intangible costs and benefits of computer capital and we present several new empirical results based on this model. Using eight years of data for 820 non-financial firms in the United States, we find that an increase of one dollar in the quantity of computer capital installed by a firm is associated with an increase of about ten dollars in the financial markets' valuation of the firm. Other forms of capital do not exhibit these high valuations.

Our model suggests that adjustment costs and intangible assets may provide an explanation for the high market valuation found for computers in this study as well as the high returns found for computer capital in firm-level productivity studies. Costly investments in software, training and organizational transformations that accompany computer investments can be regarded as creating intangible assets. These intangible assets do not appear on firms' conventional balance sheets but they can produce both higher market valuations and apparent "excess" returns. The empirical evidence suggests that the vast majority of the costs and benefits of computerization are embodied in otherwise unobserved intangible assets.

We thank Brownyn Hall, Robert Hall, Lorin Hitt, Stephen Oliner, and participants of NBER Productivity Seminar for valuable comments. The National Science Foundation, the MIT Center for Coordination Science, the Stanford Computer Industry Project, NationsBanc Montgomery Securities and IBM Research provided generous financial support and International Data Group and Computer Intelligence Corporation provided valuable data. The authors are responsible for any remaining errors. This paper subsumes a previous version that was presented at the *International Conference on Information Systems*, Atlanta, GA, December, 1997.

1. Introduction

Information Technology and Investment Theory

For the last three decades the U.S. corporate sector has invested in computers at an astonishing rate. According to a recent document by Bureau of Economic Analyses (BEA, 1998), the real investments in computers grew by 33.7% per year for the last three decades, 1967 - 1997. The nominal investment also showed an annual 13.4% increase for the same period. An obvious reason for this rapid investment growth is the substitution towards computers, the price of which has fallen dramatically at an annual rate of 16%. Jorgenson and Stiroh (1995, 1998) argue that the computers' contribution to economic growth mainly comes from the massive substitution due to their price decline. While the effects of substitution are undoubtedly large, some economists believe that other forces hold sway. Helpman (1998) suggest that the computer engineering is one of the general purpose technologies, which are characterized as a "drastic innovation" and has "a potential for pervasive use in a wide range of sectors." The pervasive use of a general purpose of technology in other sectors can stimulate "innovational complementarities" (Bresnahan and Trajtenberg, 1995).

Dictated by the Moore's law on the supply side and enabled by the ever-increasing applications on the demand side, the price decline of computers has been prolonged for the last half a century and is projected to continue at least another decade. This rapid and lasting price decline is substantially greater than that experienced by any other general purpose technologies (Lipsey, Kekar and Carlaw, 1998). These combined economic forces of substitution and complementary innovation appear to have been associated with higher output and productivity growth by adopting firms (Brynjolfsson and Hitt, 1993, 1995; Lichtenberg, 1995), and may have been foreseen by the stock market as early as 1973. (Greenwood and Jovanovic, 1999).

Although the theories and anecdotes about the "information technology revolution" abound, some observers are still skeptical about the promise of computers. The skeptics point out that the portion of computer hardware in total capital stock still remains quite small. According to the above BEA document, computers' nominal share in fixed private capital is a mere 0.86% in 1997. When Solow initiated the discussion on the "computer productivity paradox" in 1987, the computer share was even lower.[1] Oliner and Sichel (1994) concluded that any computer revolution was still too early to detect given the small share of computer hardware, although they projected a greater real impact of computers in the future.

Our paper presents new and substantially larger measures for the size of the assets that may be related to computers. Applying the q-theory of investment with minor modifications and analyzing firm-level financial data, this paper presents evidence that the estimated average q for computer hardware appears on the order of 10. This number looks surprisingly large, considering the prediction of the original q-theory of investment, which states that the equilibrium value of marginal q for reproducible assets should be unity, since the firm purchases or builds its assets until the costs of reproducing the assets reach their financial markets' valuation (Tobin, 1969). While it can be difficult to pin down the source of this high valuations, we will present evidence suggesting computer related intangible assets may be responsible. We will also suggest that the intangible assets are composed of capitalized adjustment costs, and other intangible assets correlated with computers such as software, new business practices and other complementary organizational innovations to exploit benefits of computer technology.

Capitalized adjustment costs of investment are one of the intangible assets, which the firm's accounting books do not capture. After Tobin's conjecture, Abel (1977), Yoshikawa (1980), and Hayashi (1982) recognized that if adjustment costs incur during capital installation with a convex adjustment cost function in investment, the marginal q

---

[1] Solow quipped, "You can see computer age everywhere but in the productivity statistics." in Solow, R. M. (1987) "We'd Better Watch Out." New York Times Book Review, July 12, p.36.

should become one plus the marginal installation costs.[2] Values of q greater than one reflect "short-term rents" that are earned by the installed capital and persist until the installation completes (Abel, 1990; R. Hall, 1999). The source asset of the rents is the stream of past adjustment costs. For the case of computers, of which investments are ever growing, the "short-term rents" can appear to last longer, as the investment opportunities have been lasting for several decades.

In addition to adjustment costs, another important source of higher q is increasingly recognized. If the accounting rules and conventions do not correctly capture all the firm's productive assets, then the calculated average q, of which the denominator is the firm's assets, apparently goes up. Following conservative accounting rules and traditions, the firm's balance sheet does not usually include valuable intangible assets such as research and development (R&D) investments, brand equity, firm specific human capital, and organizational assets. For example, the U.S. generally accepted accounting principles (GAAP) require immediate expensing of R&D investments. The advertisement costs to build the brand equity, on-the-job-training costs to improve employees' human capital, and costs to reorganize the firm's structure and practices to adapt itself to new technologies or to changes in demands all fail to appear as assets on the balance sheet. We may call this failure *investment mismeasurement* problem, in comparison to output mismeasurement emphasized by Griliches (1994). In the modern economy where not only the intangible outputs but also intangible intermediate goods become increasingly predominant, the conventional emphasis on physical capital accumulation exacerbates the measurement problem when assessing costs and benefits of economic activities.

Recognizing the shortfalls of the conventional emphasis on physical and tangible assets, some researchers have attempted to estimate the size of some of these intangible assets

---

[2] While the marginal q is not directly observable, observable average q, calculated essentially as the market value of all securities of the firm divided by its accounting book value, equals to the marginal q under special but important conditions. As Hayashi (1982) pointed out, the average q is equal to marginal q, when the firm is a price-taker and the firm's production technology and investment installation technology are constant return to scale. However, if the firm is a price-maker with constant return to scale technologies, then the average q is higher than the marginal q; the higher average q reflects the monopoly rents.

through market value measure rather than simply accepting the accounting records. For example, Jorgenson and Fraumeni (1995) documented a large underestimation of human capital investments in the U. S. economy; the investments in human capital far exceed investments in physical capital for the post-war period. They estimated the size of the human capital investments by assuming that the workers' market wage is the return on their human capital, concluding human capital investment share exceed non-human share by a factor of five. A similar idea of estimating valuable intangible assets through market valuation of the firm is found in R.Hall (1999). Hall's formalization of "quantity revelation theorem" states, "with competition and constant return to scale, and no adjustment costs, the value of the firm equals the quantity of capital." While the theorem itself is a direct consequence of the first order conditions of neoclassical optimal investment rule, Hall goes further than just stating the conditions under which the quantity revelation theorem holds. He suggests that the market "value of corporate securities, interpreted as a measure of the quantity of capital, behaves reasonably" for the period of 1945 – 1998. The firm's valuable intangible assets beyond the physical assets are "technology, organization, business practices, software, and the other produced elements of the successful modern corporation." More importantly, the size of these intangible assets can be reasonably approximated by the difference between the value of the firm's all financial securities and the tangible capital stock recorded in the accounting book.

Hall's quantity revelation theorem can be conceptually extended when adjustment costs exist. The short-term rents from installed capital can be seen as returns on the capitalized adjustment costs, which behave as valuable assets. In addition, the perfect competition assumption for the quantity revelation theorem may also be relaxed, interpreting the monopoly rents as returns on scarce assets the firm possesses. These scarce assets may result from various origins such as the economies of scale on direct or indirect externalities. In any case, it is increasingly recognized that modern firms possess considerable intangible assets. In particular, in this paper we will focus on computer related intangible assets.

Business Environment and Information Technology

A major theme of research in the field of information systems has been that computers and other types of information technology (IT) enable new ways of organizing, at the level of the work group, the firm, and even the whole industry (Malone, Yates and Benjamin, 1987). Furthermore, numerous case studies have documented that simply overlaying computer investments on old ways of doing business often leads to disappointing results. For instance, Orlikowski (1992) found that providing workers with access to Lotus notes did not automatically lead to increased sharing of information; new incentive systems, training, and patterns of interaction also needed to be developed. It may be no coincidence that the past decade, which has witnessed a significant increase in real computer investment, has also been accompanied by substantial restructuring of firms and even industries.

Important as they are, knowledge and information assets do not show up on most firms' balance sheets. Instead, some of these are manifested in the shared learning, organizational design, and communications architecture that transmit information within and across functions. In particular, investments in information technology are often accompanied by parallel “investments” in human and organizational capital.

If the intangible assets really exist, the resulting effect on the firm's market valuation should be measurable, even when the underlying assets are not directly observable. The financial markets, which heed the discounted value of future revenues, provide a valuable indicator of whether CEO's decisions to make these investments are generating value for the owners of the firm. Specifically, if a firm needs to make investments in intangible assets in order to unlock the full value of computer capital, then the market value of a firm with substantial computer assets already in place should be greater than that of a similar firm that has not yet integrated computers into its organization. A computer that has been leveraged with complementary intangible assets should be significantly more valuable to a business than a computer in a box on the loading dock.

Excess Return of Computer Capital and its Market Valuation

In addition, this approach has the potential to solve an open puzzle regarding the economic effects of information technology. The puzzle follows from the discovery that computer capital appears to be persistently associated with higher levels of output than other types of plant and equipment. As shown by Brynjolfsson and Hitt (1993, 1995) and Lichtenberg (1995) and others, estimates of production functions on large samples of data consistently find that the gross marginal product – the increase in output associated with each dollar of input – is substantially higher for computer capital than for other types of capital. A more detailed survey of this literature can be found in Brynjolfsson and Yang (1996).

If merely investing in IT did actually create more value than other investments, an inescapable question arises: why don't rational managers simply invest more in IT until these excess returns are all captured, driving down the marginal product of the computer capital? Or as Robert Gordon put it: “if IT has excess returns, what is the hidden force that prevents greater investments?”[3] One explanation for this puzzle is that the high levels of output associated with computer investments reflect not only the contributions of computers, but also the contributions of costly, but unmeasured intangible assets that coincide with investments in computers. While these intangible assets are overlooked in standard production functions, they may be just as real as other assets in their ability to generate value. In other words, the output increases associated with computer capital are not necessarily “excess” returns, but rather reflect returns on a collection of partially unmeasured assets.

Because none of the previous studies explicitly included intangible assets in the production functions that they estimated, value created by these assets would tend to show up in the coefficients of other variables, such as computer capital. As noted in

---

[3] In his published comments on Oliner and Sichel (1994).

several of these studies, this suggests that computer capital can be thought of as a "marker" for a broader set of investments which include not only tangible computer hardware, but also software, organizational routines, relationships and human capital which are associated with the measured computer investments (See e.g. Brynjolfsson and Hitt, 1995). If intangible assets are an important contributor to firms' output, and if they tend to be correlated with investments in computers, then this could explain the persistently high levels of output associated with computer capital in empirical research.

Our analysis of data from 820 non-financial firms over 8 years finds evidence that the financial markets do in fact value each dollar of computer capital at about ten times the valuation placed on a dollar of conventional capital. Not only do computer-related intangible assets exist, but also they appear to be very large. The remainder of the paper is organized as follows. In section 2, we summarize some of the relevant empirical research. In section 3, we discuss the derivation of the estimation equations from a dynamic optimization model in which computers have *intangible correlates* as well as adjustment costs. In the fourth section, we present the several empirical results using various data sources and regression exercises. Detailed discussion about the results and a new look on the old productivity puzzles are presented in the conclusion. The last section discusses the possible sources of the computer-related intangible assets and their implications for the economic growth and the stock market appreciation. The role of software-related costs in the formation of the intangible assets are discussed in detail.

2. Related Empirical Research

As noted above, there have been numerous studies that have examined the relationship between computers and productivity at the firm level. While the early work on small samples did not find a productivity impact (Loveman 1994; Barua, Kriebel & Mukhopadhyay 1991), the more recent work has consistently found a positive correlation between computers and productivity and between computers and output, as noted above.

In contrast to the growing number of studies focused on output measures, there is little research that investigates the relationship between IT capital and market value. Dos Santos and others showed that an announcement of innovative IT investments had positive effects on the stock market. However, since a non-innovative IT investment was associated with negative stock price movement, the overall effects of IT investment announcement resulted in zero effect among their sample of firms (Dos Santos, Peffers and Mauer, 1993).

In addition to the IT oriented literature, the empirical part of this paper draws on another research tradition. Many researchers in economics and business have used stock market valuation as an alternative measure of business performance. Especially in the literature on the economics of R&D, estimating the stock market valuation of R&D capital is a common strategy. Griliches (1981) pioneered the use of this measure of R&D performance and B. Hall (1993a, b) documented declining R&D market value in the 1980s. B. Hall (1999) reviews the issues from the recent studies of the R&D and market value. The growing accounting literature on the valuation of intangible assets is also relevant to our research. For example, Lev and Sougiannis (1996) documented value-relevance of R&D expenditure to investors. Using the earnings data and the stock market data, they showed that R&D spending should not be expensed but should be treated as intangible assets and amortized accordingly. This paper's empirical estimation equations are similar to those of Griliches or Hall, except of course, that we add computer capital as an explanatory regressor. In addition, this paper discusses models used by Griliches and Hall, and presents comparative results from various functional forms. The theoretical base and derivation of equations of this paper rely on papers by Tobin (1969), Lucas (1967), Hayashi (1982), Wildasin (1984), Hayashi and Inoue (1991), and R. Hall (1999).

3. Econometric Model and Data

Discussions on the Estimating Equations

This subsection is a simpler variation of Wildasin (1984) and Hayashi & Inoue (1991). We add some auxiliary derivations needed for the discussion of this paper, especially to incorporate intangible assets correlated with certain types of tangible assets. Following earlier work, we assume that firms face the following dynamic optimization problem.

(1) $$\underset{I}{Maximize}\ V(0) = \int_0^\infty \pi(t)u(t)dt$$

(2) where $$\pi(t) = (F(K,N,t) - \Gamma(I,K,t)) - N - I$$

(3) given $$\frac{dK}{dt} = I - \delta K$$

Here a firm maximizes its objective function, market value *V(0)* at time t = 0, which is equal to the profit stream $\pi(t)$ discounted by factor *u(t)*. The decision variable is the investment vector I, and the constraint is the depreciation rule given in the equation (3). *F(K,N,t)* is the amount of output the firm can produce using capital input vector equal to *K* and variable input vector equal to *N*. The adjustment costs takes the form of lost output $\Gamma(I,K,t)$. The depreciation rate of the capital good K_j is given by δ_j, and δK denotes a vector of which i-th element is $\delta_j K_j$ All the variables except for time *t* and depreciation rate δ are in dollar value.

As shown in the appendix A, under some technical assumptions; we can decompose the value of a firm into several components assigned to its several types of physical capital. A detailed derivation and sufficient conditions under which this result is possible are presented in appendix A. The following decomposition derived from the firm's optimization problem will be the basis to estimate the intangibles in our econometric study.

(4) $$V(0) = \Sigma_j \lambda_j K_j(0)$$

In this framework the source of the value multiplier λ_j is *the accumulated adjustment costs*; i.e. $(\lambda_j-1)K_j$ is the size of intangibles originating from the costly adjustment process of capital K_j. Because V and K_j are directly observable, the λ_j can be estimated using econometric methods.

One stylizable fact about the size of intangibles is that the market valuation (λ_j) of capital K_j is higher when the investment rate was higher, ceteris paribus. This result comes from the first order condition, $\lambda_j = u(1+\Gamma_I)$, and the convexity assumption of our adjustment cost function Γ. This model suggests that even when there is nothing special about the computer capital except for its rapid investment rate, we should observe higher λ for computer capital. There may be another source of higher adjustment costs of computer investment. As computer technology is a new general-purpose technology, computer investments may accompany considerable changes in the structure and behavior of organizations. In our model, Γ_I for computer capital is higher than that of other types of capital, and the higher Γ_I may also result in larger λ. If it is costly to install computer capital, the installed capital should earn more.

Accumulated Adjustment Costs versus Unmeasured Correlated Intangibles

In the above subsection we applied the q-theory of investment with convex adjustment cost function and argued that the accumulated adjustment costs can be considered intangible assets. In addition to the accumulated adjustment costs, there may exist other intangible assets that do not originate from the adjustment process of the computer hardware. Empirically, it is not simple to disentangle the intangible assets coming from adjustment process and those from other sources. For example, software expenditure can be thought of as either adjustment costs or unmeasured investments correlated with computer hardware investments. Possibly, software expenditure for the operating systems or network management programs can be thought of as adjustment costs, which is essential for computers and their connections to run properly in offices and factories. On the other hand, software expenditure for statistical process control may be considered intangible investments that moderately relate to the adjustment process of computer hardware.

Nonetheless, at least conceptually we may separate these two types of intangibles – accumulated adjustment costs versus non-adjustment intangibles correlated with computer hardware, although the empirical distinction is not straightforward. Let us name the non-adjustment intangibles correlated with computers as *intangible correlates* of computers, which is different from intangibles coming from adjustment process. In this section we extend our analysis to a more general case where the computer related intangible assets originate both from adjustment process and the intangible correlates of computers. In a sense, the intangible correlates represent a pure mismeasurement problem.

Let us assume that we can measure the physical capital precisely (K_j), but there exist non-adjustment intangible assets perfectly correlated with each types of physical capital. The size of these *intangible correlates* is assumed $(\nu_j - 1)K_j$ for the corresponding capital K_j. We also assume that these intangible correlates' depreciation rates are exactly same with those of their corresponding physical assets. Then the new output function and the Hamiltonian for the modified problem can be stated as follows:

$$Y(\nu K, L, \nu I, t) = F(\nu K, L, t) - \Gamma(\nu K, \nu I, t) \tag{5}$$

$$H(\nu I, \nu K, N, t) = (F(\nu K, N, t) - \Gamma(\nu I, \nu K, t) - N - \nu I)u(t) + \lambda(\nu I - \sum_{j=1}^{J} \delta_j \nu K_j) \tag{6}$$

Here the ν is a vector of which j-th element is ν_j. Under this formulation, the $Y(\cdot)$, $F(\cdot)$ and $\Gamma(\cdot)$ all remain homogeneous functions of the first degree in all their arguments -- K, L, and I. All the results afterwards are straightforward as in the above subsection and appendix A, but the market valuation equation becomes:

$$V = \Sigma_j \ \nu_j \lambda_j K_j \tag{7}$$

Here our estimated coefficients will correspond to $\nu_j\lambda_j$ instead of λ_j. Notice that using this estimation alone we cannot empirically discern the effect of accumulated adjustment costs (λ) from that of intangible correlates (ν).

Observed Excess Marginal Product of Computer Capital

The observed gross marginal product of capital K_j is the following. We will drop the subscript j and time t hereafter for simplification. Substituting νK and νI with K* and I*, the apparent gross marginal product of capital K is:

$$Y_K(\nu K, N, \nu I) = \nu F_{K*}(K*, N) - \nu \Gamma_{K*}(I*,K*)$$

Here the subscripts denote the first order partial derivative with respect to K and K^*. Applying the Euler's theorem to Γ, a homogenous function of the first degree in its arguments, we have:

$$Y_K = \nu(F_{K*} - \Gamma_{K*}) = \nu[F_{K*} - (-\Gamma_{I*} (I^*/K^*) + \Gamma/K^*)] = \nu[F_{K*} + \Gamma_{I*} (I^*/K^*) - \Gamma/K^*]$$

Subtracting the normal return, $F_K(K,L)$, from this, we have the *apparent excess marginal product (AEMP)*:

$$\begin{aligned} AEMP &= Y_K(\nu K,N,\nu I) - F_K(K,L) \\ &= [\nu F_{K*} - F_K(K,L)] + \nu\Gamma_{I*}(I^*/K^*) - \nu\Gamma/K^* \end{aligned}$$

Each term in this equation has a corresponding economic interpretation. The first term, $[\nu F_{K*} - F_K]$, is the return on the unmeasured intangible correlates. The second term, $\nu\Gamma_{I*}(I^*/K^*)$, is the return on the intangible assets coming from the *past* adjustment costs. The third term, $\nu\Gamma/K^*$, is the loss of marginal product due to the *current* adjustment costs. The first term is always positive when the intangible correlates are positive; and so is the second term, $\nu\Gamma_{I*}(I^*/K^*)$, when the adjustment costs are increasing in investment. On the contrary, the third term, $-\Gamma/K^*$, is always negative whenever the adjustment costs are positive.

Interestingly, the sum of last two terms depends on the shape of adjustment cost function, particularly on the degree of convexity. Let us consider a special but informative case; when $F = cK^{\eta}L^{1-\eta}$ and $\Gamma(I,K) = dI^{1+\alpha}K^{-\alpha}$. Under this Cobb-Douglas technology, the parameter α determines the degree of convexity for the adjustment costs; the larger α, Γ becomes more convex in investments. Here, the following is a matter of algebra:

$$\begin{aligned} \mathit{AEMP} &= (\nu^{1+\eta}-1)\, c\eta K^{\eta-1}L^{1-\eta} + \nu d\alpha(I/K)^{1+\alpha} \\ &= (\nu^{1+\eta}-1)\, F_K(K,L) + [\nu\alpha/(1+\alpha)]\, \Gamma_I(I/K) \end{aligned}$$

The first line of the equality comes from the direct substitution of F(K,L) and Γ(I,K); and the second line results from $\Gamma_I = d(1+\alpha)(I/K)^{\alpha}$. The same formula holds if just one type of capital has positive intangible correlates and other types of capital do have zero intangibles either from correlated assets or adjustment costs. In addition, under the assumption of constant returns to technology η is the factor share of computers. For our present purposes, this is small enough to justify the following approximation. Hence the excess marginal product can be approximated as:

$$\text{(8)} \qquad \mathit{AEMP} \approx (\nu-1)F_K(K,L) + [\nu\alpha/(1+\alpha)]\, (\lambda - 1)(I/K)$$

Notice that if the adjustment cost function is convex, i.e. $\alpha > 0$, then adjustment costs' contribution to apparent excess return is positive, while if the adjustment cost function is near $\alpha \approx 0$, then adjustment costs' contribution to apparent excess return is near zero, leaving only the contribution of intangible correlates. We will discuss this matter further in section 5.

Econometric Issues of Market Valuation

The equation (7) of the above section represents our basic estimation equation, which equates the value of the firm to the shadow value of the capital assets *after* they are in place:

(7') $V = \Sigma_i \lambda_i K_i$

where λ_j is the shadow value (including both adjustment costs and intangible correlates) of one unit of capital asset j . If there are two types of capital, computers (c) and other capital (k), then (λ_c–1) would represent the difference in value between computer capital which is fully integrated into the firm vs. computers which are available on the open market, and (λ_k – 1) would be the corresponding value for other types of capital.
To translate the result of the optimization model into a specification suitable for empirical testing, we need to specify the different types of capital that we will consider and a set of additional control variables (X) that are likely to influence the market value of firms. Including an error term, ε, we have our estimation equation:

$$(9) \qquad V_{it} = \alpha_i + \sum_{j=1}^{J} \lambda_j K_{j,it} + X_{it}\gamma + \varepsilon_{it}$$

Here, i, t, j are indices of firms, time, and different capital goods, respectively. The coefficients to be estimated are (vectors) α, λ and γ.

We divide assets into three categories: computers, physical assets (property, plant and equipment), and other balance sheet assets (receivables, inventories, goodwill, cash, and other assets). For the other control variables (X) we will use the ratio of R&D capital to assets, the ratio of advertising capital to assets and time. Advertising and R&D captures other types of nonstandard assets that have been considered in prior work.

$$(9)' \quad V_{it} = \alpha_i + \lambda_c K_{c,it} + \lambda_p K_{p,it} + \lambda_o K_{o,it} + controls + \varepsilon_{it}$$

Here K_c, K_p, and K_o represent computer capital, physical capital, and other balance sheet assets, respectively. In some specifications, we will combine the physical capital and other balance sheet assets into one category, non-computer capital, in order to mitigate the effect of multicolliniarity between different types of assets. In addition, in some specifications for robustness checking, we will use different measures of market value and non-computer capital; current assets and current liabilities are subtracted from the non-computer assets and market value, respectively. In a sense, if we want to concentrate on the the relationship between market value of a firm and its productive assets, this approach makes more sense, as the current assets such as cash and account receivable are rarely productive assets.

There are some issues about the data and the specification that warrant concern. First, although our level specification is derived from a theory with reasonable assumptions, it tends to accentuate the heteroscedastisty of stochastic terms. We will address the problem by using a generalized (or weighted) least squares technique (GLS) to dampen the influence of large residuals. Another way to address the problem is to use different functional forms that assume multiplicative error structure instead of additive error structure assumed in equation (9). Elasticity specification (log-linear specification), or non-linear estimation as in Griliches' original specification serve to the purpose. In addition, to control for heterogeneity among firms and to gauge the robustness of our results, we will also perform the estimates using fixed effects, and "between" regression which enables us to separate out effects due to variation over time for the same firm and effects due to variation across firms. In addition, we can use robust regression techniques (least absolute deviation - LAD) that are less sensitive to outliers of all sorts. More importantly, the apparent higher valuation of computers may result from spurious correlation of computer investments and market value of firms. We will discuss the possibility exploiting implications from the fixed effect models, short and long difference models, and Granger causality models.

Data Sources and Construction

The data set used for this analysis is a panel of computer capital and stock market valuation data for 820 firms over the 1987-1994 time period. A brief description of each data source follows with additional detail in the data appendix.

Computer Capital: The measures of computer use were derived from the Computer Intelligence Infocorp installation database that details IT spending by site for companies in the Fortune 1000 (approximately 25,000 sites were aggregated to form the measures for the 820 companies that represent the total population in any given year). This database is compiled from telephone surveys that detail the ownership for computer equipment and related products. Most sites are updated at least annually with more frequent sampling for larger sites. The year-end state of the database from 1987 to 1994 was used for the computer measures. From this data we obtain the total capital stock of computers (central processors, personal computers, and peripherals). The computer data do not include all types of information processing or communication equipment and are likely to miss that portion of computer equipment that is purchased by individuals or departments without the knowledge of information systems personnel.[4] There is other smaller computer capital data set compiled by International Data Group (IDG). The IDG data set has been used by Brynjolfsson and Hitt (1993, 1995) and Lichtenberg (1995) for productivity analyses. We will present regression results with IDG dataset for the purpose of robustness checking. The IDG data covers 339 firms for the period of 7 years from 1988 to1994.

Other Capital and Control Variables. Compustat data was used to construct stock market valuation metrics and provide additional firm information not covered by other sources. Measures were created for total market value (market value of equity plus debt), property, plant and equipment (PP&E), other assets, R&D assets, and advertising expense.

Overall, the full dataset includes 820 firms and 4620 observations over 8 years for market value and computer capital stock.

4. Results

Basic findings and alternative hypotheses

The basic ordinary least square (OLS) regression analysis (estimate of equation 9) for calculating the effect of computer on market value is shown in the first column of Table 1a. The results show that each dollar of property, plant and equipment (PP&E) is valued at about a dollar, and a dollar of other assets such as account receivables and inventories is valued at about $0.7. Strikingly, each dollar of computer capital is associated with over $16 of market value. According to our model, this implies that the stock market imputes an average of $15 of "intangible assets" to a firm for every $1 of computer capital. All capital stock variables are significantly different from zero, and the high R^2 (~87%) suggests that we can explain much of the variation in market value across firms with our model.[5] In the remaining part of this section, we will discuss results from various model specifications, in which possible bias, specification errors, and alternative hypotheses that may generate our OLS estimates are addressed.

An alternative cause that may explain the high valuation of computers is a spurious correlation between computers and unobserved firm specific variables such as scare assets, good management, or growth opportunity that may contribute to market valuation. For example, if we suppose a firm with high market valuation tends to invest in computers following fads regardless of their productivity, we have an alternative

---

[4] Another potential source of error in this regard is the outsourcing of computer facilities. Fortunately, to the extent that the computers reside on the client site, they will still be properly counted by CII's census.

[5] Among control variables R&D to asset ratios and advertisement to asset ratios are not always significant. Firm effects, industry effects, and year effects, as separate groups are always strongly significant.

hypothesis. To probe this question, we will discuss three estimation models: fixed effect models, difference models, and Granger causality models. Some interesting implications are observed in the results in addition to the test for the spurious correlation.

First we investigate how much the correlation between market value and computer investment is driven by variation across firms, (a "between" regression) and variation for the same firm over time (a "within" or "firm effects" regression). If the response to an experiment with correct model specification were immediate, then the “within” estimates and the “between” would be the same. If the estimates from different specifications differ, we may conclude a specification error; and the within result should be used as a better estimate of the true parameter. However, in the case of lagged response experiment as in computer investments, within estimation may produce a lower bound of true value.[6]
We find that both “within” and “between” sources of variation are important but the effect due to variation between firms is larger. While the "between" regression implies a market value of computer capital of $20, for the within regression, this value is $5.6 with year control as shown in the second column of Table 1a, and $6.9 without year control in the third column. The R-squares for the fixed effect models reach above 97%.

The within regression can be interpreted as removing all the effects that are unique to a particular firm but constant over the sample time period. Thus, the lower value for the within regression suggests that factors unique to specific firms, such as the organizational, human and strategic context, are important in determining the market value of computers. However, the fact that the coefficient remains fairly large and significant also implies that computers are not simply proxying for some unrelated firm characteristic like "good management", except to the extent that it changes with a firm's computer capital stocks. Similarly, the firm dummies in the within model may capture

---

[6] Consider a hypothetical experiment, where N/2 individuals, half of the sample, are treated and the rest are not. Suppose the treatment effect for the treated is perfect with one period lag and last only one period. For the non-treated the effect is zero. The experiment is repeated T times, and we observe the panel of N individuals for T period. For the observed data, the within regression produces zero effect result, while between estimate correctly captures the treatment effect.

firm-specific monopoly rents, so the within model suggests there exist computer related intangible assets beyond any firm specific characteristics including monopoly rents.

The results from the difference models in Table 1b can further justify our discussion on the fixed effect models. Overall, as we move from one-year differences to seven-year differences, the coefficient on IT generally rises from $3 to about $8, with a small dip at fourth differences. The physical capital coefficient rises from one-year differences to three-year differences and then stays level at approximately $1.2. If the higher valuation of computers resulted from the spurious correlation between firm specific characteristics and computer investment, the difference specification would wipe out the high valuation.

In addition to cleaning up firm-specific effects, the incremental rise in the computer coefficient when the difference length increases from one year to seven years favors our intangible asset hypothesis over a short-term rent hypothesis. As R.Hall (1999) pointed out, in the short run the installed capital earns scarcity rents from capitalized adjustment costs during the time gap between the identification of opportunity and actual realization of the investment. Since the computer investments are growing rapidly, the high computer coefficient may reflect the short-term scarcity rents from adjustment processes. If this be the case, we would observe a decreasing computer coefficient as the difference length increases, as the short-term rents are dissipating over the long run. On the contrary, our results support the hypothesis that computer investments accompany a series of complementary investments after the installation of computer hardware. Finally the results from difference models may also raise another alternative hypothesis: varying adjustment speed across different assets may produce an upward bias in estimates of computer coefficient. If computer capital adjusts within one year while another takes two years, then the variation in adjustment speeds may significantly influence coefficient estimates in short differences, but become unimportant when larger time horizons are considered. Once again, the result in Table 1b says the contrary, favoring our intangible hypothesis over this alternative.

In addition to the fixed effect models and difference models, we test the reverse causality more directly using Granger's (1969) suggestion. As shown in Table 1c, either in the "simple causation models" or in the "instantaneous causation models," market value does not "Granger cause" computer investments. On the other hand, the computer investments have prediction power for the market value increase in the future. If we rule out the possibility of manager's private information about the future market value appreciation, the results in Table 1c once again support the intangible hypothesis.

Robustness of estimates

The above subsection addressed the concerns on the possible alternative explanations of high computer coefficient. In this subsection we discuss the robustness of our results to assumptions regarding residual structure, functional forms. We will also discuss the robustness to outliers, sample splits, and other data source. In Table 2a, we examine how robust our results are to variations in econometric methods. For this analysis we restrict the sample to a balanced panel[7] to get data consistency and apply different regression techniques: generalized least squares (GLS) to control for heteroskedasticity, and least absolute deviation regression (LAD)[8]. Overall, the basic results are consistent whether we use balanced or unbalanced panels and whether we correct for heteroskedasticity or outlier problem using GLS or LAD in both between and within regressions.[9]

Table 2b presents regression results from various functional forms. Here we divide capital stocks into two categories (computer capital and non-computer capital) instead of three. Furthermore, the right hand side variable is the market value less current debt, the left hand side non-computer asset is total assets less current assets and less computer capital,

---

[7] We exclude all firms that are missing any data in any year, reducing the sample size from 4,620 to 3,312 observations.

[8] LAD regression minimizes the absolute value of the deviation of the actual and fitted values, as opposed to the square of the difference as is done for OLS. Standard errors for the LAD estimates are done using bootstrapping techniques with 100 repetitions to obtain the empirical distribution of the coefficient estimates.

[9] While White test suggests a strong size-based heteroskedasticity, the results are changed very little with alternative estimation methods.

following the convention used in B. Hall (1993a, b) and Griliches (1981). As we discussed in the data section, this approach may better capture the relationship between productive assets and market value. We lost 600 observations during the data preparation due to the lack of relevant items in the Compustat dataset. Estimating these models we use SIC 1.5 digit codes instead of SIC 2 digit codes as industry control.[10] The reason for this reduction of industry category is pure estimation consideration: the non-linear estimation of the third column becomes increasingly unstable when we use 42 industry categories instead of 11. The coefficient estimates for linear and log-linear models with 1.5 digit dummies and 2 digit dummies do not differ with statistical significance.

The first column is the result from our base-line direct linear model with the reduced data set:

$$V = \lambda_c K_c + \lambda_n K_n + \text{controls} + \varepsilon; \qquad \text{c for computers, n for non-computers}$$

The results are qualitatively similar to the first column of Table 1a. The slightly larger coefficient of computers result from two factors: one from data, the other from specification. First, without current debt and current assets, this model's data has arguably better economic meanings. Secondly, the multicollinarity among different types of assets is mitigated in this model.

As B. Hall (1999) observes, one advantage of this specification is that the linear model assumes the shadow value for each type of capital is the same across firms, which is a more reasonable assumption than the elasticity equalizing assumption in the following log-linear specification.

$$\ln(V) = \beta_c \ln(K_c) + \beta_n \ln(K_n) + \text{controls} + \varepsilon$$

---

[10] We broke down the SIC 1 digit category further. While the mining and manufacturing covers SIC 1000 – 3999, we use 7 categories instead of 3.

In addition to the constant elasticity assumption, the log-linear model also assumes that the coefficient of one type of capital heavily depends on the level of other type of capital stock, which unlike in the production function is less justifiable in this context. On the other hand, there exist econometric merits in this specification; the original log-normal distribution of variables are converted to normal distributions so that the coefficient estimates are more stable with less heteroscedasticity. The effects of outliers are also mitigated in this model, and as a result we have a better fit. The OLS estimation of the log-linear specification gives shadow value estimates for both types of assets similar to the linear specification.

The third column of Table 2b presents the non-linear estimation results from Griliches's (1981) original specification. B. Hall (1993a) also uses the same specification. This model is just a log transformation of our baseline linear specification with multiplicative error structure.

$$V = (\gamma_n K_n + \gamma_c K_c)^{\delta} e^{\varepsilon}$$

By log transformation, this becomes

$$\text{(10)} \quad \ln(V) = \delta \ln(K_n) + \delta \ln(\gamma_n + \gamma_c K_c/K_n) + \varepsilon$$

Griliches (1981) and Hall (1993a) assume $\delta = \gamma_\eta = 1$, and take the linear approximation of $\ln(1+x) \approx x$, so as to estimate the following simple model.

$$\ln(V) = \ln(K_n) + \gamma_c (K_c/K_n) + \text{controls} + \varepsilon$$

We discuss the implications of this linear approximation in detail in the R&D discussion below and in the Appendix C. Our strategy is to directly estimate equation (10) by non-linear least squares with the assumption of $\delta = 1$. The computer coefficient is smaller than in the linear model or in the log-linear model, but not far apart.[11]

Table 2c presents results from IDG dataset instead of CI dataset. As in the above subsection, here again we use the new market and asset measures, and divide the asset categories into two: computers and non-computer assets. The coefficient estimates are 15-30% lower across specifications than those of Table 1a, but qualitatively similar. IDG dataset contains only 1167 observations, which is about a quarter of CI dataset's observations, and comprises larger firms. The IDG dataset's computer capital measure comes from self-reported estimates of the market value of computer hardware by information systems manager, and averages twice as large as the CI dataset's measure. A more detailed analysis on the IDG data is found in Yang (1994), in which other functional forms are also explored.

The computer capital's market valuation may differ across industries. The left half of Table 2d shows the result of manufacturing versus non-manufacturing sample split exercise. There is no statistically significant difference in computer capital coefficients, which suggests that the adjustment costs are not significantly different across industries. This is consistent with the finding of Brynjolfsson and Hitt (1995) that the productivity effects of computerization do not differ statistically between manufacturing and non-manufacturing, as well as case study evidence on the commonalities in the uses of computing across industries. The right half of Table 2d is the time dimension sample split. The first half comprises data from 1987 to 1990, and the second half from 1991 to 1994. There is some evidence that computer capital's valuation may have dropped during 1990's, but the difference in computer capital coefficients across time is not statistically significant at the 5% level.[12] Table 2e also presents the year-by-year estimation. The coefficients in all years are similar to those from between models.

---

[11] The non-linear estimation often did not converge, and sometimes gave local convergent results.

[12] However, we can reject the joint null hypothesis that all assets' coefficients are the same, which may, in part, reflect the consequences of the recession during the early 1990s.

These regressions provide strong support for our hypothesis -- computers are associated with a substantial amount of intangible assets. Our estimates imply that these intangible assets dwarf the directly measured value of computer hardware that shows up on the balance sheet. In addition, the results on non-computer capital are consistent with prior expectations and research; most other assets are worth approximately a dollar. Finally, the difference between the "*between*" and "*within*" regressions suggests substantial effects of firm-specific characteristics on the value of computer capital, which is consistent with production function estimates of IT's marginal product (Brynjolfsson and Hitt, 1995).

Market Valuation of Computers and R&D Investment

As discussed in Section 2, this paper's market valuation equation is similar to Hall's (1993a, b) and Griliches's (1981). According to B. Hall (1993a), the market valuation of R&D capital has fallen during the 1980s. For the entire sample period from 1973 to 1991, her market value estimate of R&D capital is 0.48, which indicates sub-par valuation. During the seventies the market to book ratio of R&D capital was roughly one-to-one; but during the late eighties and early nineties the ratio dropped to the range of .2 – .4.

Our matched sample of firms with computers and R&D investments comprises only 250 firms in manufacturing, which is one-tenth of the size of B. Hall's data and less than half of our full sample. The R&D capital is constructed by the same procedure with 15% depreciation rate described in B. Hall (1990), and used in B. Hall (1993a, b).

The first two columns of Table 3a document the pooled estimation coefficients of various types of capital. The first column is the result from all manufacturing companies in our full sample. The second column documents the same regression results for those companies that reported R&D spending in Compustat. Again, computer's coefficient is around 18, and those of physical capital and other balance sheet assets are 0.9 and 0.7, respectively. The last three columns of Table 3a report the market valuation results including R&D capital. Here we combine both non-computer assets into one, because including too many variables causes a problem with multi-collinearity. With or without R&D, computer coefficient remains high, as shown in the center and last column of Table 3a. Without computers, R&D capital's market valuation is 0.32, very similar to B. Hall's result. Including computers makes the R&D coefficient no longer significant. In Table 3b, we replicate B. Hall's (1993a, b) result with the same log-ratio specifications. Somewhat lower computer coefficient in this specification is hardly surprising, considering the approximation imbedded in the model and other econometric issues. In Appendix C, we detail the discussion on the R&D regressions.

5. Discussion and Conclusions

The main finding of the paper is that the financial market puts a very high value on installed computer capital. Market valuations for each dollar of installed computer capital are on the order of ten times greater than the market values for each dollar of conventional assets. This finding is robust to different data sources, numerous different estimating equations, and various functional form specifications. The high financial market valuation for computer capital is visible in both manufacturing and services industries and in both the 1980s and the 1990s.

Sources of Computer Related Intangible Assets

This subsection discusses possible sources of the computer-related intangible assets. The regressions suggest that there exist about nine dollars of computer-related intangible assets for each dollar of computer hardware in the typical firm. What are the possible sources of the intangible assets? A natural candidate is the capitalized value of purchased and internally-developed software. Another important candidate is the capitalized value of the costs that firms incur when implementing organizational changes to harness the potential of computerization.

The distinction between hardware and software is more elusive than it seems, and also the software-related costs are sometimes closely related to organizational change. Portions of software packages such as operating systems, utility programs, and even some application programs are developed and installed before all the hardware shipment is complete; and the firm's accounting convention often treats many of these costs as expenses rather than capital investments. In addition, some software-related costs such as person-hours of outside consultants and internal employees are sometimes hard to disentangle from costs to reengineer firms' business processes. Finally, the costs of computer-associated business process redesign, organizational restructuring and strategic reposition include not only outside consultants' time, but also significant management effort and employee retraining. Again, these costs are typically treated as expenses even when they are expected to create long-lived revenue streams. Nonetheless, we can get a sense of the magnitudes of these costs, and the implicit capital stocks created, using available data. Combined with the econometric estimation above, this provides an indication of the size and composition of the intangible assets associated with computerization.

According to Oliner and Sichel (1994), the income share of the software is about 70% of that of the hardware, which is in turn about 2% of all private non-residential capital stock in the United States. They also provide estimates of the investments in software and the depreciation rate for software, and accordingly this suggests that the size of the nation's software capital stock is comparable (about 80%) in magnitude to that of the hardware capital stock. In other words, the value of intangible assets coming from software could account for about one dollar among nine dollars of computer-related intangible assets.

A study by Gurbaxani (1990), who relied on IDG survey of computer industry from 1976 to 1984, documented information systems budget shares of firms' information systems department. He showed that the shares for computer hardware (38%), software (28%), and computer services labor (34%) remained stable during the period. Recent survey results by IDG and other research institutes for the ratio of software to hardware do not tell a very different story. Various estimates of budget share of hardware among all the information systems budget items hover around 40%. A recent IDG report (1995) and a survey by Strassmann (1999) documented that software and related services account for 50% to 60% percent of all information technology spending during the period of 1987 to 1998. Combining Oliner and Sichel's argument with these recent data, we may conclude that there are at the most about one dollar of software related assets for each dollar of computer hardware.

One caveat, however, is that we might have underestimated the software assets developed in-house. A substantial portion of internal computer services labor is devoted to developing and maintaining business application software. OECD (1998) report on the software sector documented over 50% of software spending is allocated to the in-house development. If the in-house software has similar characteristics in terms of depreciation and cost structure, then we missed out up to a whole dollar worth of assets coming from the internally developed software. Hence, we may have up to one additional dollar of intangible assets in the form of in-house software.

There is another reason to believe that we may still have underestimated the software component of intangible assets. Experiences of software deployment such as ERP (Enterprise Resource Planning) systems have demonstrated substantial costs incurring during the deployment and adaptive maintenance of the software. The cost analysis of ERP by Gormley et al. (1998) is summarized in Table 4. Their data is based on a survey of 51 firms in the Fortune 1000 list. If we took the face value of the numbers in Table 7 and assume the value can be applicable to all the packaged software, then the true investment required to deploy a packaged software applications such as an ERP system would become seven times as large as the purchase value of the software application itself (6.5 = \$3.2/\$20.8). As the package software comprises about 30% of the total non-hardware spending, the deployment costs of software could be roughly three times of the total direct software costs (2.65 = 0.7 + 0.3*6.5). If one assumes these deployment costs create assets with comparable service lives as the hardware and software involved, then the resulting "assets" could be up to four times as large as the hardware assets themselves.[13] However, a careful look at the Table 7 reveals that the above estimation stated above may involve some double counting. For example, $2.25 million dollars of internal staffers' salary (= 30 persons * $100,000/person * 9/12 year) for implementation could have been recorded already in the book as the internal software costs; $7.2 million dollars of external consultants' compensation (= 30 persons * $1200/day * 200 days) could have been expensed as the software service purchase accounts. Similar costs for the deployment are also prone to similar double counting. Thus most of $20.8 million start-up costs for a $3.2 million worth of an ERP suite could have been already accounted for in the form of internal information systems labor or the outside purchase of computer services.

Besides the double counting, there are additional aspects of the ERP's cost structure worth a careful look. The person-hours of both internal and external staffers are not solely devoted to improving the software. More important aspects of their job are rather to redesign the information flows and task flows, i.e. business processes, to exploit the potential of the ERP system. In other words, external and internal staffers for the implementation and deployment of a ERP suite are not building the software systems, but are reorganizing the business processes. The ERP software adapted to and running in Federal Express cannot be easily ported to UPS, given the different computer hardware and organizational infrastructure, hence most of it is not re-sellable in the software market. The firm-specific portion of the implementation is very high, and the created assets are highly specific.

To summarize, even when using the most generous estimates for the size of software assets, they can account for at most 3-4 dollars out of every 9 dollars of intangible assets associated with computers. A recent BEA document report the software investments comprise 87% of hardware in 1987, and 129% in 1994 (Survey of Current Business, November, 1999). The majority of the computer-related intangible assets remain to be

---

[13] Three dollars of packaged software plus a dollar of in-house software for each hardware dollar.

explained. Our deduction is that the main portion of the computer-related intangible assets comes from the new business processes, new organizational structure and new market strategies, which each complement the computer technology. Many researchers and practitioners have documented the difficulties of transforming organizations to exploit a new technology. A recurrent theme in this literature is the idea that computers will not help us produce more of the same things in the same way as allow us to do entirely new things in new ways (Hammer, 1990; Hammer and Champy, 1993; Malone and Rockart, 1991; Orlikowski, 1992). More recent studies (Brynjolfsson and Hitt, 1998; Bresnahan, Brynjolfsson and Hitt, 1999) provide direct evidence that computer use is complementary to new workplace organizations which include more decentralized decision making, more self-managing teams, and broader job responsibilities for line workers.

As IT is a new technology still being developed rapidly, IT investments may accompany considerable changes in the structure and behavior of organizations. Not only are the costs of IT-enabled organizational change large, but there is a very real risk of failure.[14] Including these risks, the expected costs of embarking on a significant IT-based restructuring can be daunting. A pessimist might bemoan these organizational costs, while an optimist is likely to celebrate the assets that are implicitly created in the process. Our model suggests that they are *both* right – confirming the maxim that “there is no free lunch”. Ironically, the very costs that firms incur when they undertake the organizational changes associated with computer using are the same factors that create barriers for competitors seeking to match the investment.

Wal-mart’s main assets are not the computer software and hardware, but the intangible business process they have built around those computer systems. As computer technology is an important enabler to reengineer their business process, we can observe the high market valuation of their computers. Amazon’s web site and the computer hardware infrastructure are only a small portion of their total assets, but the accompanying business model and business process that support the model are quite valuable. The following quote by Denise Caruso suggests that seemingly simple idea of setting up a "cool" web site is not enough for success. Amazon needed to invent a whole new way of doing business in order to add real value to their computer technology. Simply adding web technology to a traditional company would not have achieved the same results.

> "Amazon's on-line account maintenance system provides its customers with secure access to everything about their account at any time. They can ...customize virtually everything about the system to their own tastes... Such information flow to and from customers would paralyze most old-line companies."[15]

The formal relationship between hidden costs and intangible asset values can be shown formally, as we do in the section 3. However, the test of this hypothesis is that the stock market values a firm's installed computer capital much more highly than the equivalent amount of computer capital on the open market, before it has been integrated into any firm. For the high market valuation of installed computer capital to persist across eight years and across different sectors of the economy, it must reflect commensurately high costs of adjustments and integration. If not, firms would simply purchase more computer capital and arbitrage away any difference between the value of installed computer capital and computers on the open market.

We could enumerate some other candidates for the computer-related intangible assets. For example, compare the value of disk storage to the value of data in that storage. Although there are scant studies on the issue available, we can presume that the value of the business data about customer information, supplier information and business knowledge is several times as large as the costs of disk storage itself. How much is the value of these alternative sources of intangible assets? We simply don't know yet. In any

---

[14] A leading proponent of computer-enabled "re-engineering" have estimated that up to 70% of all such efforts fail (Champy, 1995).

[15] Denise Caruso, New York Times, p. C5. May 11, 1998

event, while the nine-to-one ratio for computer-related intangibles vs. the hardware itself may seem strikingly large, it is quite consistent with the case evidence of computerization efforts in a variety of contexts.

“Excess” Returns on Computer Hardware

The very high marginal product of computer capital that has been found in studies by Brynjolfsson and Hitt (1993,1995), Lichtenberg (1995), and Krueger (1993) can also be explained using the same framework. In the short run, after higher adjustment costs have already been incurred, the installed computer capital and its intangible correlates contributes more to output than other types of capital, simply to compensate for the higher costs previously incurred as part of the investment. In other words, the existence of adjustment costs leads to "excess" returns to already-installed capital. More importantly, in addition to the adjustment costs, we argued that computer investment might also be correlated with investment in various types of largely invisible assets. These assets tend to accompany its more visible partner, computer capital, bestowing higher returns wherever it is found. In equilibrium, the combined assets consisting of computer hardware plus intangible assets may well earn normal returns, but if only the computer capital is actually measured, then computer capital appears to be earning excess returns.

Each of these types of computer-related intangible assets can provide a direct explanation for Gordon’s puzzle raised in response to the recent studies documenting computer capital’s excess return. He asked, if computers were more productive than other assets, “what friction or market failure prevented these firms from investing even more in computers until the returns were driven down to those on other types of capital?”[16] The apparent high return on computers may be the normal return on intangible assets closely related to computers.

---

[16] In a comment on Oliner and Sichel (1994).

In section 2, we tried to distinguish two sources of these intangibles*:*1) *intangible correlates* and 2) *accumulated adjustment costs*. Under Cobb-Douglas technology, the apparent excess marginal product is:

$$(8) \qquad AEMP \approx (\nu\text{-}1)F_K(K,L) + [\nu\alpha/(1+\alpha)]\,(\lambda - 1)(I/K)$$

The gross marginal product by Brynjolfsson and Hitt (1995) and Lichtenberg (1995) ranges from 80% to 200%. Combined with the preceding analysis, these values can help us approximate the size of the intangible assets associated with computers. Given the high user cost of capital for computer hardware, the normal gross marginal product of computers could be around 30% - 40%. Taking the 120% for the estimated gross marginal product and 40% for the normal gross marginal product of computers, we can practically set the upper bound for ν value in the above equation (8) to three. If the adjustment cost function is near linear, then the intangible correlates comprise two dollars out of total nine dollars of intangible assets for each dollar's worth of computer hardware. If we take the high end value of 200% as computer's apparent marginal product, then the upper bound of ν becomes five. To literally take these values, we may conclude that the both the intangible correlates and capitalized adjustment costs need to be substantial to make the computer coefficient ten.

On the other extreme, if we believe that the all intangibles come from adjustment process, then the α can be estimated around 0.35, which implies modest convexity with the power of 1.35. One important result to note in this exercise is that even if the market valuation of computers is ten times higher than the ordinary capital, we cannot necessarily expect to observe a marginal product for computer capital that is ten times higher. The measured marginal product of computers will depend on the convexity of the adjustment cost function for computers and the amount of intangible correlates of computers relative to adjustment costs. In any case, our model and evidence support the hypothesis that installing computers not only requires adjustment costs, but also that it can create a valuable, but less visible, assets in the process.

Computer-related intangible assets, economic growth, and the stock market

This subsection discusses important implications of the computer-related intangible assets for the economic growth accounting and the recent stock market surge. Quite a large portion of economic growth figure during the last two decades and the rapid stock market appreciation during the last decade may be attributable to these computer-related intangible assets. Let us consider each case relying on previous studies combined with simple back-of-the-envelope calculations.

Let us consider computer hardware capital's growth contribution numbers given by Oliner and Sichel (1994), and Jorgenson and Stiroh (1995). According to Oliner and Sichel, the average annual contribution of computers to the U.S. economic growth is 0.21% for the period of 1980-1992. Jorgenson and Stiroh's numbers are a little higher, as they used different assumptions on the depreciation of the computer capital's service. They attributed 0.52% of annual growth to the computer capital for the period of 1979-1985, and 0.38% for the 1985-1992 period.

According to the conventional framework of growth accounting, the growth contribution of any input equals the product of nominal income share and the growth rate of the input's stock. The income share of computers by Oliner and Sichel is about 0.9% during the period of 1980-1992. If we believe that the computer-related intangibles are ten times as much as the computer hardware, the income share of those intangible assets should be about 8%. Let us suppose that the growth rate of the computer-related intangible assets be the same with the growth rate of *nominal* investment in computers. This presumption is a direct consequence of our framework presented in section 3. According the BEA data, the annual growth rate of nominal investment in computer hardware averages 7.8% for the period from 1980 to 1992. The income share (8%) and the imputed growth rate (7.8%) suggest that the annual contribution of these computer-related intangible assets to the US economic growth averages 0.62%. Combined with the 0.21% contribution from computer hardware, the annual growth of 0.83% can be attributable to all the computer-related assets, tangible and intangible. As the growth rate of nominal investments in computers accelerated to an annual 14% during the recent period (1992-1998), a similar back-of-envelope calculation results in an annual growth contribution from computer-related intangible assets over this period of well over 1%. This suggests that during the 1990s, the total growth of the productive capacity of the US economy may have been much larger than previously assumed.

Similar consideration can be done for the stock market appreciation. During our sample period of 1987–1994, the mean of market value for a firm in our balanced panel increased by 84%, from \$5.0 billion to \$9.2 billion. The computer capital increased by six-fold, from \$16 million to \$96 million. Using our estimates of computer capital's market valuation, we can ascribe the portion of total increase of \$4.2 billion to the increase of computer-related assets. Using our estimate of λ =10, we may conclude that about 20% of this market value appreciation can be viewed as the contribution of computerization. Since the debt value is not as responsive as the stock value to the financial market's valuation of assets, we may suppose that the stock valuation captures most of the valuation for the computer-related assets. During the same period, the mean stock market value of our sample of firms increased by 77%, from \$3.6 billion to \$6.3 billion. Among this 2.7 billion increase, 30% can be attributed to all the computer-related assets, tangible and intangible.

These results provide quantitative support for the hypothesis that computers have an economic impact that is far larger than their relatively small direct share of the capital stock. Any assessment of the role of computers in the U.S. economy will need to take account of the intangible assets associated with computerization.

Table 1a. Effects of Various Assets on Firms' Market Valuation
Baseline Regressions of Different Models

Market Value	Pooled	Fixed Effect Within		Between
	OLS	w/Year	wo/ Year	OLS
Computer	16.391***	5.616***	6.876***	20.334***
Capital	1.271	0.902	0.913	3.001
Physical	0.974***	1.134***	1.227***	0.957***
Capital	0.021	0.054	0.053	0.037
Other	0.685***	0.826***	0.826***	0.660***
Assets	0.009	0.012	0.012	0.019
Controls	R&D** Adv Year*** Industry***	R&D Adv Year*** Firm***	R&D Adv Firm***	R&D Adv Industry***
R^2	0.8727	0.9704^{A}	0.9711^{A}	0.8740
Observations	4620	4620	4620	4620

Key: * - p<.1, **- p<.05, *** - p<.01
A: Excluding fixed effect variance when calculating R^2, R^2 = 0.723, 0.716 for fixed effect models.

Table 1b: Short and Long Difference Estimations

	Differences						
Market Value	1 year	2 years	3 years	4 years	5 years	6 years	7 years
Computer	2.949***	4.644***	5.523***	6.539***	4.041***	4.746***	7.806***
Capital	1.031	1.332	1.611	1.655	1.710	1.757	2.370
PP&E	0.368***	0.695***	0.973***	1.244***	1.226***	1.240***	1.206***
	0.074	0.079	0.083	0.089	0.093	0.099	0.133
Other Assets	0.863***	0.852***	0.828***	0.837***	0.853***	0.848***	0.728***
	0.013	0.017	0.019	0.021	0.020	0.020	0.029
Controls	year*** industry***	year*** industry***	year*** industry***	year*** industry***	year*** industry***	Year* industry***	NA industry***
Observations	2898	2484	2070	1656	1242	828	414
R squares	0.66	0.62	0.66	0.71	0.77	0.84	0.86

Table 1c: Leads and Lags between Changes in Market Value and Computer Investments

Computers (0)	Simple Causal Model	Instantaneous Causal Model		Market Value (0)	Simple Causal Model	Instantaneous Causal Model
Computers (-1)	-0.103	-0.104		Market Value (-1)	-0.108	0.009
	0.128	0.127			0.197	0.128
Computers (-2)	-0.019	-0.037		Market Value (-2)	0.144	0.004
	0.172	0.170			0.151	0.050
Computers (-3)	1.120***	1.123***		Market Value (-3)	0.045	0.054
	0.231	0.228			0.065	0.070
Market Value (0)		0.0010		Computers (0)		5.960***
		0.0006				2.137
Market Value (-1)	0.0014	0.0014		Computers (-1)	14.665***	0.597
	0.0010	0.0010			4.722	4.526
Market Value (-2)	0.0006	0.0006		Computers (-2)	16.546***	16.565
	0.0018	0.0018			5.864	14.700
Market Value (-3)	0.0001	0.0001		Computers (-3)	-3.578	-10.701
	0.0006	0.0006			16.759	16.209
Controls	year*** Industry***	year*** Industry***		Controls	Year*** Industry***	year*** Industry***

- All variables except controls are in yearly changes

Table 2a: Effect of Various Assets on Firms' Market Valuation
Balanced Panel Only, Between and Within Regressions

	Between Regression			Fixed Effect Within Regression	
	OLS	GLS	LAD	GLS	LAD
Computer	22.285***	18.540***	14.824***	5.584***	4.308***
Capital	4.193	1.464	3.545	0.921	1.154
Physical	0.968***	1.014***	0.984***	1.244***	1.169***
Capital	0.049	0.016	0.019	0.055	0.113
Other	0.654***	0.656***	0.652***	0.811***	0.814***
Assets	0.024	0.010	0.088	0.015	0.086
Controls	R&D Adv* Industry***	R&D*** Adv*** Industry***	R&D*** Adv*** Industry***	R&D Adv Year*** Firm***	R&D Adv*** Year*** Firm***
R^2	0.892	0.869	0.675	0.681	0.836
Observations	3312	3312	3312	3312	3312

Table 2b: Effect of Various Assets on Firms' Market Valuation
From Various Functional Specifications

Level or Log of Market Value	Models	Linear Specification	Elasticity Specification	Griliches-Hall Non-Linear Spec. (NLS estimation)
Computer Capital	Coefficient	21.913***	0.120***	15.223***
	Std. Error	1.219	0.010	0.079
	Market Value	21.913	19.921	15.223
Non-Computer Assets	Coefficient	1.130***	0.760***	1.179***
	Std. Error	0.014	0.011	0.079
	Market Value	1.130	1.185	1.179
Controls		R&D*** Adv.*** Year*** Industry***	R&D*** Adv.*** Year*** Industry***	R&D*** Adv.*** Year*** Industry***
R^2		0.7589	0.7971	0.7806
Observations		3950	3950	3950

- 1.5 SIC digit Industry Category is used.

Table 2c. Alternative Data Source, IDG

Market Value	Pooled OLS	Fixed Effect Within w/Year	Fixed Effect Within wo/ Year	Between OLS
Computer Capital	10.805***	4.962***	5.723***	16.730***
	1.115	0.827	0.818	2.568
Non-Computer Capital	1.079***	1.291***	1.553***	1.027***
	0.035	0.099	0.088	0.057
Controls	R&D** Adv*** Year*** Industry***	R&D*** Adv* Year*** Firm***	R&D*** Adv Firm***	R&D Adv Industry***
R^2	0.7773	0.9461	0.9429	0.8035
Observations	1167	1167	1167	1167

Table 2d: Split Sample (robust standard errors)

Market Value	Manu-facturing	Non-manu-facturing		First Half	Second Half
Computer Capital	17.689***	20.740***		21.655***	13.829***
	4.075	6.401		9.168	3.608
Physical Capital	0.903***	0.994***		0.925***	1.014***
	0.075	0.067		0.065	0.097
Other Assets	0.726***	0.399***		0.663***	0.698***
	0.043	0.056		0.040	0.062
Controls	R&D** Adv.** Industry*** Year***	R&D Adv. Industry*** Year***		R&D Adv. Industry*** Year***	R&D Adv Industry*** Year***
R^2	0.894	0.819		0.907	0.863
Observations	2989	1631		2179	2441

Table 2e: Year-by-Year Fluctuation of Market Valuation (robust standard errors)

Years	1987-88	1989-90	1991-92	1993-94
Computer	28.435^{***}	15.966^{***}	21.082^{***}	11.965^{***}
Capital	3.962	3.483	3.647	1.665
Physical	0.821^{***}	0.994^{***}	1.024^{***}	0.989^{***}
Capital	0.027	0.034	0.048	0.042
Other	0.655^{***}	0.672^{***}	0.661^{***}	0.719^{***}
Assets	0.015	0.015	0.022	0.015
Controls	R&D*** Adv Year Industry***	R&D** Adv** Year Industry***	R&D Adv Year Industry***	R&D Adv Year** Industry***
R^2	0.907	0.909	0.840	0.887
Observations	1090	1089	1182	1259

Table 3a: Computers and R&D (Level Specification)

Market Value	All Manu-facturing	R&D Companies		R&D Companies			
					Computer	R&D	Both
Computer	17.689***	17.724***		Computer	21.349***		20.908***
Capital	1.507	1.688		Capital	1.597		1.646
				R&D		0.317***	0.084
				Capital		0.076	0.076
Physical	0.903***	0.863***					
Capital	0.025	0.033		Physical +	0.835***	0.860***	0.827***
Other	0.726***	0.736***		+ Other Assets	0.008	0.011	0.010
Assets	0.010	0.011					
Controls	R&D** Adv.** Industry*** Year***	R&D** Adv.** Industry*** Year***		Adv.** Industry*** Year***	Adv.** Industry*** Year***	Adv.** Industry*** Year***	Adv.** Industry*** Year***
R^2	0.894	0.912		R-square	0.917	0.91	0.917
Observations	2989	1920		Observations	1920	1920	1920

Table 3b: Computers and R&D (Log-Ratio Specification)

	All Manu-facturing	R&D Companies		
Log(Market Value)		Computer	R&D	Both
Log(Physical Capital)	0.910***	0.909***	0.904***	0.908***
	0.008	0.009	0.009	0.009
Computer/Physical Capital	2.263***	2.217***		0.834***
	0.209	0.246		0.251
R&D/Physical Capital			0.250***	0.218***
			0.019	0.021
Controls	Adv.** Year*** Industry***	Adv.** Year*** Industry***	Adv.** Year*** Industry***	Adv.** Year*** Industry***
R^2	0.844	0.877	0.882	0.883
Observations	2989	1920	1920	1920

Table 4. Typical Cost Structure for A ERP Suite: Start-up and Ongoing Costs

Start-up Costs		$millions
Software	ERP application Suite License (HR, Financials, Distribution) 1,000 regular trained users, 2,000 casual users	$3.2
Hardware	Application, Web, and database servers including storage	$0.8
Implementation	9 months to complete pilot site including process engineering, apps configuration, and testing 30 external consultants as $1,200 a day 30 internal staffers at an average salary of $100,000 Services to license ratio 3 to 1	$9.3
Deployment	3 external consultants at 9 sites for 3 months 9 internal staffers at each site for 6 month 5 days of user training at an average burdened user salary of $50,000 3 full-time training staff at an average burdened salary of $100,000	$7.5
Start-up Costs Total		**$20.5**
Annual On-going Costs Total		**$9.4**
	Software and Hardware	$0.6
	Ongoing customization and integration	$3.3
	User Support and Training	$1.6
	On-going customization and integration	$3.3
	Upgrades	$0.8

Source: Gormely et al. (1998)

Appendix A: Derivation of the Estimation Equation

The Hamiltonian of the optimization problem (1), (2), (3) can be given:

(A.1) $H(I,K,N,t)=(F(K,N,t)-\Gamma(I,K,t)-N-I)u(t)+\lambda(I-\delta K)$

Here the Lagrangian multiplier vector λ represents the shadow value vector of one unit of each capital good; i.e. λ_j is the shadow value of capital good K_j. If the valuation of financial markets is correct, λ_j is the value of one additional unit of capital good K_j. Our interpretation is that λ is the value sum of one unit of physical capital and intangible assets associated with that physical capital.

We assume the following to make the analysis simple.

(A1) $F(K,N)$ and $\Gamma(I,K)$ are linear homogeneous functions over (K,N) and (I, K) respectively.

(A2) $\Gamma(I,K)$ are twice continuously differentiable in I and K. $\Gamma(0,K) = 0$, and $\Gamma(I,K) \geq 0$; $\Gamma_I > 0$, and $\partial^2\Gamma/\partial I\partial I'$ are positive definite.

A1 is equivalent to constant returns to scale assumption; A2 captures the shape of adjustment cost function. It is increasing and convex in investment. This shape ensures the existence of the solution. The first order conditions of the Hamiltonian under these assumptions can be given:

(F1) $F_{N_l}-1=0$, for all l, where l = 1, 2, . . ., L, the index of variable inputs.

(F2) $\lambda_j-(\Gamma_{I_j}+1)u=0$ for all j and t, where j = 1, 2, . . ., J, the index of capital inputs.

(F3) $\dot{\lambda}_j=-(F_{K_j}-\Gamma_{K_j})u+\lambda_j\delta_i$ for all j and t

And the transversality condition is:

(F4) $\lim_{t\to\infty}\lambda(t)K(t)=\lambda(\infty)K(\infty)=0$

Let us consider economic interpretations of these conditions. F1 is the familiar marginal productivity condition: the dollar values of marginal product of inputs equal to its dollar value of the input. F2, $(1+ \Gamma_I)u = \lambda$, means that discounted total cost of unit of investment is the shadow value of that capital. Now from the transversality condition, we can write:

$$\lambda_j(0)K_j(0) = \lambda_j(0)K_j(0) - \lambda_j(\infty)K_j(\infty) = -\int_0^\infty (\dot{\lambda}_j K_j + \lambda_j \dot{K}_j)dt$$

Using the three first order conditions of the maximization problem, we get the following equation (A.2); and applying Euler's theorem to $\pi(\cdot)$, as it is homogeneous of degree one in K, I and N, we obtain the equation (A.3):

$$\text{(A.2)}\quad \begin{aligned} &-(\dot{\lambda}_j K_j + \lambda_j \dot{K}_j) \\ &= (F_{K_j}K_j - \Gamma_{K_j}K_j - \Gamma_{I_j}I_j - I_j)u \end{aligned}$$

$$\text{(A.3)}\quad \begin{aligned} &\sum_{j=1}^{J}\lambda_j(0)K_j(0) = \int_0^\infty \left[\sum_j^J (F_{K_j}K_j - \Gamma_{K_j}K_j - \Gamma_{I_j}I_j - I_j) + \sum_l^L (F_{N_l}N_l - N_l)\right]u(t)dt \\ &= \int_0^\infty ((F-\Gamma) - N - I)u(t)dt = \int_0^\infty \pi(t)u(t)dt = V(0) \end{aligned}$$

We now have the equation to decompose the value of a firm into several components assigned to its several types of physical capital, (A.3) $V(0) = \Sigma_j \lambda_j K_j(0)$.

Appendix B: Data Description

The variables used for this analysis were constructed as follows:

IT Capital. We have a direct measure of the current market value of the firms' computer equipment as reported by Computer Intelligence Corp. The market value was constructed for each model of computers. Computer Intelligence calculates the current market value, the replacement cost, of computers using their current market value table of computer equipment.

Physical Capital. The source of this variable is Standard Poor's Compustat Annual Dataset. We consider two options to construct the variable. The first is to construct the variable from gross book value of physical capital stock, following the method in (Hall, 1990). Gross book value of capital stock [Compustat Item #7 - Property, Plant and Equipment (Total - Gross)] is deflated by the GDP implicit price deflator for fixed investment. The deflator can be applied at the calculated average age of the capital stock, based on the three year average of the ratio of total accumulated depreciation [calculated from Compustat item #8 - Property, Plant & Equipment (Total - Net)] to current depreciation [Compustat item #14 - Depreciation and Amortization]. Another method is just to use the net physical stock depreciation [calculated from Compustat item #8 - Property, Plant & Equipment (Total - Net)]. In productivity literature the first method should be used, but in market value estimation we adopt the second approach for the consistency with market value and other assets, which is measured in current dollars. The dollar value of IT capital (as calculated above) was subtracted from this result.

Other Assets. The other asset variable is constructed as the total asset [Compustat Annual Data item #6] minus physical capital constructed above. This item includes receivables, inventories, cash, and other accounting assets such as goodwill reported by companies.

R&D Asset Ratio. Constructed from R&D expenses [Compustat annual item #46]. Interestingly, this item includes software expenses and armortization of software investment. R&D stock is constructed using the same rule as in Hall (1993a, b), including a 15% depreciation rate. The final ratio is just the quotient of the constructed R&D stock divided by total assets. Less than half of firms in our sample report R&D expenses. The missing values were filled in using the average of the same industry (SIC 4-digits).

Advertising Asset Ratio. Constructed from advertising expenses [Compustat annual item #45]. Less than 20% of our sample of firms report the item. The same rule with R&D assets ratio is applied.

Market Value. Fiscal year end's common stock value plus preferred stock value plus total debt. In Compustat mnemonic code, it is MKVALF + PSTK+DT, which represents total worth of a firm assessed by the financial markets.

Appendix C. R&D Regressions

Table 3a and 3b report similar regression results with a different specification. Specifically, in Table 3b we examine the log-ratio specification used by Griliches (1981) and Hall (1993a). The regression of Table 3b is the replication of B. Hall's including computers. As shown in the third column, the R&D's market valuation is 0.25, which is similar to Hall's result for the late 1980's and early 1990's, although our sample size is just one-tenth of hers. The computer coefficient using this specification drops considerably to 2.3. In addition, adding R&D capital reduces computer coefficient even further to 0.8.

The sharply lower computer coefficient in this specification is not surprising and does not contradict the earlier results. This specification relies on an approximation, $\log(1 + x) \sim x$ for small x. This approximation makes high intensity R&D firms or heavy users of computers more inaccurate. Specifically, the estimation equation assumes

$$log(1+ \beta_C\, C/K + \beta_R\, R/K) = \beta_C\, C/K + \beta_R\, R/K.$$

Griliches's or Hall's derivation of this specification is as follows. A firm's market value is the value of physical capital plus intangible assets:

$$V = K + \beta_1 C + \beta_2 R, \text{ with multiplicative error term.}$$

Here K is the physical capital, C is the computer capital and R is the R&D capital. Log transformation of the above equation gives:

$$\begin{aligned} logV &= log(K + \beta_1 C + \beta_2 R) + \varepsilon \\ &= logK + log(1+ \beta_1 C/K + \beta_2 R/K) + \varepsilon \\ &\sim logK + \beta_1 C/K + \beta_2 R/K + \varepsilon \end{aligned}$$

Relaxing the restriction that physical capital has a coefficient of one, and adding constant terms and control variables, we have an estimation equation:

$$logV \quad = \alpha + \beta_K \, logK + \beta_C \, C/K + \beta_R \, R/K + Controls + \varepsilon$$

Observe the approximation: $log(1+ \beta_C \, C/K + \beta_R \, R/K) = \beta_C \, C/K + \beta_R \, R/K$.

If beta's or the ratios of C/K and R/K are high, then the approximation becomes increasingly difficult to justify. Our estimate of β_C was 20. For a mean firm, our estimate of β_1 C/K was nearly 40 %, which is well above the range of justifiable small value. Especially, this approximation becomes disproportionately worse for high intensity firms of R&D or computers. As a result, the coefficients will be lowered by this stretching of x-axis without corresponding changes in the y-axis. In our sample some high computer intensity firms have the C/K ratio as high as 50%. If we assume the true computer coefficient to be ten, for such firms the approximation, $log(1+ \beta_C \, C/K) \sim \beta_C \, C/K$, results in a very large error.

The size of the bias can be illustrated by considering various sub-samples of the data. In fact, when we restrict the sample of firms to those with $C/K < 5\%$, (98.4% of the sample), the computer coefficient increases to 5.3, with a similar p-value. When we use 72.5% of the sample including firms with $C/K < 3\%$, the computer coefficient increases to 14; and when we use 60% of the sample with $C/K < 2\%$, the coefficient increases to twenty, the same as in the level specification.

REFERENCES

Abel, A. B. (1977). "Investment and the Value of Capital," Ph.D. Thesis, Massachusetts Institute of Technology.

Abel, A. B. (1990). "Consumption and Investment," Chapter 14 in B. Friedman and F. Hahn (eds.) Handbook of Monetary Economics, North-Holland. pp. 725-778.

Barua, A., C. Kriebel, and T. Mukhopadhyay (1991). “Information Technology and Business Value: An Analytic and Empirical Investigation.” University of Texas at Austin Working Paper, May.

Bresnahan, T., E. Brynjolfsson and L. M. Hitt (1999), “Information Technology, Work Place Organization and the Demand for Skilled Labor: Firm-Level Evidence,” NBER Working Paper No. 7136.

Bresnahan, T. and M. Trajtenberg (1995). "General Purpose Technologies: Engines of Growth," Journal of Econometrics 65:83-108.

Brynjolfsson, E. and L. M. Hitt (1993). "Is Information Systems Spending Productive? New Evidence and New Results." Proceedings of the 14th International Conference on Information Systems, Orlando, FL.

Brynjolfsson, E. and L. M. Hitt, (1995) “Information Technology as a Factor of Production: The Role of Differences Among Firms”, *Economics of Innovation and New Technology*, vol. 3, January.

Brynjolfsson, E. and L. M. Hitt (1998). "Information Technology and Organizational Design: Evidence from Firm-level data.” MIT Sloan School Working Paper.

Brynjolfsson, E. and S. Yang (1996). “Information Technology and Productivity: A Review of the Literature.” Advances in Computers **43**: 179-215.

Bureau of Economic Analyses (BEA) (1998). Tangible Wealth, NDN-0216.

Bureau of Economic Analyses (BEA) (1999). Survey of Current Business, November.

Champy (1995). Reengineering Management: the Mandate for New Leardership. HarperBusiness, New York, New York.

Dos Santos, B. L., K. Peffers, and D. C. Mauer (1993). “The Impact of Information Technology Investment Announcements on the market Value of the Firm.” Information Systems Research **4**(1): 1-23.

Economides, N. (1996). "The Economics of Networks," International Journal of Industrial Organization, vol. 14, no. 6, pp. 673-699.

Gormley, J., W. Bluestein, J. Gatoff and H. Chun (1998). “The Runaway Costs of Packaged Applications,” The Forrester Report, Vol. 3, No. 5, Forrester Research, Inc., Cambridge, MA.

Granger, C. W. J. (1969) “Investigating Causal Relations by Econometric Models and Cross-Spectral Methods,” Econometrica 37(3), pp. 424-438.

Greenan, N. and J. Mairesse (1996). "Computers and Productivity in France: Some Evidence", National Bureau of Economic Research Working Paper 5836, November, (1996)

Greenwood, J. and B. Jovanovic (1999). "The Information Technology Revolution and the Stock Market," American Economic Review Papers and Preecedings, 89-2: 116-122.

Griliches, Z. (1981). “Market Value, R&D, and Patents.” Economic Letters **7**: 183-187.

Griliches, Z. (1984). "Productivity, R&D, and Data Constraints," American Economic Review 84-1.

Gurbaxani, V. C. (1990), Managing Information Systems Costs: An Economic Analysis of Hardware/Software Trade-Offs. Washington: International Center for Information Technologies.

Hall, B. H. (1990). The Manufacturing Sector Master File: 1959-1987. National Bureau of Economic Research Working Paper 3366.

Hall, B. H. (1993a). “The Stock Market's Valuation of R&D Investment During the 1980s.” The American Economic Review 84(1): 1-12.

Hall, B. H. (1993b). "Industrial Research during the 1980s: Did the Rate of Return Fall?" Brookings Papers on Economic Activity: Microeconomics 2: 289-343.

Hall, B. H. (1999). Innovation and Market Value. NBER Working Paper No. 6984.

Hall, R. E. (1999). The Stock Market and Capital Accumulation. NBER Working Paper No. 7180.

Hammer, M. (1990). “Reengineering Work: Don't Automate, Obliterate.” Harvard Business Review (July-August): 104-112.

Hammer, M. and J. Champy (1993). Reengineering the Corporation: a Manifesto for Business Revolution. HarperBusiness, New York, New York.

Hayashi, F. (1982). “Tobin's Marginal q and Average q: Neoclassical Interpretation.” Econometrica **50**(January): 213-224.

Hayashi, F. and T. Inoue (1991). "The Relation between Firm Growth and Q with Multiple Capital Goods: Theory and Evidence from Panel Data on Japanese Firms." Econometrica 59(3): 731-753.

Helpman, E. (1998). Introduction in Helpman E. (eds), General Purpose Technology and Economic Growth. The MIT Press, Cambridge, Massachusetts. pp. 1-14.

Hitt, L. M. and E. Brynjolfsson (1996). “Productivity, Business Profitability, and Consumer Surplus: Three Different Measures of Information Technology Value.” MIS Quarterly June: 121-142.

Hoover (1996), Hoover's Handbook of American Companies, Reference Press, Austin, TX.

IDG (1995), Worldwide Black Box: Worldwide Information Technology Spending Patterns, 1994-1999: An Analysis of Opportunities in 40 Countries, International Data Corporation, Framingham, MA.

Jorgenson D. W. and B. M. Fraumeni (1995). "Investment in Education and U.S. Economic Growth," in D. W. Jorgenson (eds.) Productivity. Volume 1. Postwar U.S. Economic Growth, Cambridge and London: MIT Press. p 273-331.

Jorgenson, D. W. and Stiroh, K. J. (1995), “Computers and Growth,” Journal of Innovation and New Technology,” Vol. 3.

Jorgenson, D. W. and Stiroh, K. J. (1998), "The Role of Computer Investment and Consumption in U.S. Economic Growth," Harvard University mimeo.

Krueger, A. (1993), “How Computers Change the Wage Structure: Evidence from Micro-Data,” Quarterly Journal of Economics 108(1).

Lev, B. and T. Sougiannis (1996), “The Capitalization, Amortization, and Value-Relevance of R&D,” Journal of Accounting and Economics, Vol. 21.

Lichtenberg, F.R. (1995) "The Output Contributions of Computer Equipment and Personnel: A Firm-Level Analysis," *Economics of Innovation and New Technology*, 3, 201-217, (1995);

Lipsey, R. G., C. Bekar and K. Carlaw (1998). "What Requires Explanation?" in E. Helpman (eds), General Purpose Technologies and Economic Growth. The MIT Press, Cambridge, Massachusetts. pp.15-54.

Loveman, G. W. (1994). An Assessment of the Productivity Impact of Information Technologies. Information Technology and the Corporation of the 1990s: Research Studies. T. J. Allen and M. S. S. Morton. Oxford, Oxford University Press**:** 88-110.

Lucas, R. E. (1967). “Adjustment Costs and the Theory of Supply.” Journal of Political Economy **75(**321-334).

Malone, T. and J. Rockart (1991), “Computers, Networks and the Corporation.” Scientific American, Vol. 265, No. 3.

Malone, T. W., J. Yates, R. I. Benjamin (1987). “Electronic Markets and Electronic Hierarchies.” Communications of the ACM 30(6): 484-497.

Montgomery, C. A., Ed. (1995). Resource-based and Evolutionary Theories of the Firm: Towards a synthesis. Boston, Kluwer Academic.

OECD (1998), The Software Sector: A Statistical Profile for Selected OECD Countries. Organisation for Economic Co-operation and Development, Paris, France.

Oliner, S. D. and D. E. Sichel (1994). “Computers and Output Growth Revisited: How Big is the Puzzle?” Brookings Papers on Economic Activity 1994(2): 273-334.

Orlikowski, W. J. (1992). Learning from Notes: Organizational Issues in Groupware Implementation. Conference on Computer Supported Cooperative Work, Toronto, Canada.

Stewart, T. (1997). Intellectual Capital. Boston, Harvard Business School Press.

Strassmann, P. A. (1990). The Business Value of Computers: An Executive's Guide. New Canaan, CT, Information Economics Press.

Strassmann, P. A. (1999). Information Productivity: Assessing the Information Management Costs of U.S. Industrial Corporations. New Canaan, CT, Information Economics Press.

Tobin, J. (1969). “General Equilibrium Approach to Monetary Theory.” Journal of Money, Credit and Banking **1(**February): 15-19.

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

Wildasin, D. E. (1984). “The q theory of Investment with Many Capital Goods.” The American Economic Review 74(1): 203-210

Yang, S. (1994). The Relationship between IT Investment and Market Value of Firms. Master's Thesis. MIT Sloan School of Management

Yoshikawa, H. (1980). "On the 'q' Theory of Investment," American Economic Review 70-4: 739-743.