

Technology Adoption Costs and Productivity Growth: The Transition to Information Technology[†]

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Abstract: Using two panels of U.S. manufacturing industries, this paper estimates capital adjustment costs from 1961 to 1996. I find that from 1974-83 adjustment costs rose sharply—they more than doubled from about 3% of output to around 7%. Moreover, this increase is specifically associated with a shift to investment in information technology. But such large adoption costs imply that the Solow residual mismeasures productivity growth: adoption costs are resource costs representing an unmeasured investment. I find that when this investment is included, productivity grew about 0.5% per annum faster than official measures during the 70's and early 80's, reducing the size of the productivity “slowdown.” Indeed, estimated productivity growth rates were roughly the same from 1974-88 as from 1949-73. Thus technology transitions critically affect productivity growth measurement.

Keywords: Technological change, productivity, adjustment cost, information technology

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I. Introduction

The literature on technology adoption is filled with examples of abrupt technology transitions. For example, U.S. railroads shifted from using mainly steam locomotives to mainly diesel locomotives in a decade [Mansfield, 1968, p. 175]. The standard technology adoption curve (“diffusion” curve) is S-shaped—very rapid adoption after a long, slow initial period. Moreover, with “general purpose technologies” [Helpman, 1998], many different industries may adopt new technologies at once. For example, many industries adopted electricity-based technologies during the 1920’s and 30’s and many adopted electronics-based technologies during the 1970’s and 80’s.

Such Schumpeterian technology transitions pose a problem for productivity measurement because such new technologies are usually new goods, that is, they are not perfect substitutes for earlier technologies. Specifically, whole new technologies may incur large adoption costs because they involve learning new skills, implementing new forms of organization, and developing complementary investments. Indeed, reviewing the recent literature on the impact of computers, Brynjolfsson and Hitt [2000] find that complementary organizational investments may be much larger than the investment in computer equipment itself. Also, information technology, in particular, often involves customization and custom-software, some of which remains unmeasured in official statistics. Because such complementary investments appear in official productivity statistics only as resource costs without the corresponding contribution to investment (and hence output), productivity may be mismeasured.

This paper estimates these adoption costs in the U.S. manufacturing sector from 1961-96 and it calculates revised productivity growth estimates based on these. Using two panels of industry data (one using 4-digit SIC industries, the other 2-digit), I obtain two main empirical results. First, I find that capital adjustment costs rose sharply during the period from 1974-83, at the same time as investment sharply shifted toward information technology (IT). Second, I find that this rise in costs is specifically associated with this change in technology. In other words, these are costs of adopting new technology.

Applying adjustment cost estimates from each panel to BLS productivity measures for the manufacturing sector, I obtain estimates of productivity growth from 1974-83 of 0.98% and 1.14%, compared to an official estimate of 0.52%. For 1974-88 the estimates are 1.45% and 1.76%, compared to 1.13%. These growth rates compare favorably to the official growth measures from 1949-73 of 1.52%, suggesting that any productivity slowdown was brief at most.

Implications and relationship to the literature

Several studies have presented models where adoption costs account for the productivity slowdown of the 70's, including Hornstein and Krusell [1996], Greenwood and Yorukoglu [1997] and Greenwood and Jovanovic [1998]. In these models, adoption costs are assumed to increase with the rate of embodied technical change. Several authors, including Gort and Wall [1998], Greenwood et al [1997], Hercowitz [1998], and Hulten [1992], have also considered the effect of embodied technical change on productivity measurement during the 70's and 80's.

Many of these studies infer a rate of embodied technical change from the slow drift between official price deflators for producer's durable equipment and Gordon's [1990] alternative estimates. But Gordon's quality-adjusted price deflators are unlikely to capture the full value of adoption costs, which are complementary investments.¹ And the resulting estimates are qualitatively quite different. Gordon's "drift" grows steadily at about 3% a year during the postwar period. My estimates of adoption costs surge sharply in the 70's (see Figure 3 below).

Several other studies have used calibrated models to explore adoption costs (or organizational costs), including Robert Hall [2000] and Michael T. Kiley [1999, 2000]. Again, the pattern emerging from my direct estimates is generally different.

The magnitude of this acceleration is important not only because it affects the calculation of productivity growth. Several of these models also relate the rise in adoption costs in the 70's to changes in wages, the skill premium and stock prices. For instance, Greenwood and Yorukoglu speculate that the growth rate of embodied technical change accelerated 2% per annum during the 70's. From this, their model implies a roughly 1.5% increase in learning costs as a share of GDP and a substantial increase in wage inequality. Yet my estimates suggest that adoption costs increased by 4% of GDP in the 70's. The implied effect on wage inequality, stock prices and other variables should also be correspondingly larger.

Another literature has attempted to assess the impact of IT on productivity, including Berndt and Morrison [1995], Chun [2001], Jorgenson and Stiroh [1999, 2000], Oliner and Sichel [1994, 2000] and Whelan [2002]. This literature suggests that the returns to IT investment were low or non-existent during the 70's and early 80's and have increased since then. This is consistent

¹ Most of the components of Gordon's index are constructed using the matched model method. Some components use hedonic regressions. Under certain conditions, hedonic deflators may partially reflect adoption costs (see below), but this only captures a portion of the adoption cost and it only applies to a small portion of total investment.

with my results for conventionally *measured* productivity. Specifically, omission of adoption costs tends to understate the effect of IT on productivity growth during the 70's.

Skepticism about the role of IT

On the other hand, the idea that IT adoption costs may be related to the productivity slowdown has generated some skepticism for several reasons:

1. IT investment is positively associated with productivity growth. Comin [2000] finds that industries that invest in IT at a higher level (relative to investment in other goods) tend to have higher productivity growth. But in my model, adoption costs are associated with the *transition* to new technology. That is, measured productivity growth is related to the *rate* of change in investment, not the *level* of investment. An industry that invests heavily in IT today may have high productivity growth, but it may also have incurred adoption costs at some point in the past when, perhaps, it made initial heavy investments in IT.

2. A second reason for skepticism is that IT equipment and software only have a small factor share, about a 3% share of cost even in 1999. This raises the question whether such a small factor can affect productivity much. For instance, Oliner and Sichel [1994] argue that computers were unlikely to exert much effect on productivity during the 80's because they had a small cost share. But this view implicitly assumes that information technology enters the production process without affecting other inputs, as some sort of surgical substitution. But much evidence suggests, instead, that computers themselves represent only a small part of the total change enabled by information technology. There is much evidence that IT is associated with deep, complementary organizational change [Brynjolfsson and Hitt, 2000, Black and Lynch, 2001]. Moreover, the new technology is introduced in information *systems*, applications that involve computers, but also many other investments. For example, in newspapers, computers replaced typewriters in the newsroom. But this permitted complementary transitions from hot metal type to phototype and from letterpress printing to offset printing. And these changes often required entire new printing plants. Thus computers (or IT equipment) comprised only a small part of the total investment in new technology, albeit the critical enabling investment. Both the adoption costs and the subsequent productivity gains were a function of the entire investment, not just the investment in computers *per se*. Below I measure the adoption costs of total investment, but I also find an association between these costs and IT spending.

3. A final reason for skepticism is the apparent recent reversal of the Solow paradox. Although during the 70's and 80's computers were found "everywhere but in the productivity statistics," the last several years have had rapid growth in real IT spending accompanied by strong productivity growth. If the productivity slowdown resulted from adoption costs, then why don't those same adoption costs cause a slowdown now?

But the relationship between adoption costs and IT spending has likely changed between 1999 and 1979. The regression analysis below provides some evidence that the IT surge of the late 90's did not have the same effect on capital quality as earlier spending. In fact, the statistical relationship between investment and productivity growth of the previous three decades appears to change during the 90's.

This effect is not surprising for at least two reasons. First, adoption costs for IT are likely a function of the number of computers (or computer terminals), not the *power* of those computers. The cost of learning a new 1,000 MHz PC system is not likely to be 40 times greater than the cost of learning a 25 MHz PC system in 1985. In fact, the learning cost on the new system may well be *less* because the greater computer power supports better software. Although the 70's saw rapid growth in the number of computers and computer terminals, most of the IT surge in the late 90's, on the other hand, arose from greater computing power per computer and more software per computer. Figure 1 charts the real share of IT investment in total investment; this surged in the late 90's. The chart also shows the share of nominal investment spent on IT hardware. This rose sharply from 1974 to 1983 but has remained more or less flat since then. Now although the cost of computing power has dropped sharply since the mid-80's, the cost of personal *computers* has fallen only slightly [Berndt and Rappaport, 2000]. This means, roughly, that the number of computers purchased relative to total investment has not changed much since the mid-80's. Hence this surge in computing power might not increase adoption costs.

Furthermore, part of the surge in the late 90's consists of greater software spending. But this might well be associated with *reduced* adoption costs. Better software is "user-friendly" and easier to learn. Also, some portion of adoption costs consists of customization and programming performed by non-programmers.² Greater software spending may represent a partial substitution of purchased software for this activity.

² The contribution of programming personnel is captured as software in the most recent official statistics [Parker and Grimm, 2000], but the activity of non-programmers is not. Historically, few personnel using computers in the early years had computer-specific job titles, and today much customization and programming activity is still performed by other occupations, e.g., economists who are SAS programmers.

More generally, much of this discussion has been framed as an examination of whether the simultaneous surge in productivity and IT investment represents a “New Economy” or just a temporary supply shock. The results here suggest a somewhat different picture: we are now well into the third decade of both strong productivity growth and strong IT investment.

The next section extends the Solow accounting framework to include adjustment costs. Then in Section III, I use this framework to obtain estimates. Section IV applies these estimates to the problem of accounting for productivity growth and Section V concludes.

II. Adoption Costs and Technology Transitions

Adjustment Costs

Adjustment costs represent a diversion of output to producing a complement of investment in capital goods. At time t

$$(1) \quad Y_t = Y_t^* \cdot (1 - c_t)$$

where Y is actual output, Y^* is potential output, and c is the percentage rate of adjustment costs, a function of investment. The absolute magnitude of the adjustment cost is $c_t \cdot Y_t^*$.

The potential output can be written using a conventional production function

$$(2) \quad Y_t^* = A_t \cdot F(K_t, L_t, M_t)$$

where A represents productivity, K is capital, L is labor and M is materials and energy. I assume constant returns to scale and competitive markets in L and M . Taking logs, differentiating and approximating assuming that $c \ll 1$ (so that $\ln(1 - c) \approx -c$),

$$(3) \quad \begin{aligned} \hat{Y}_t &\approx \hat{A}_t + \alpha_t \cdot \hat{L}_t + \beta_t \cdot \hat{M}_t + \pi_t \cdot \hat{K}_t - \frac{d c_t}{d t} \\ \alpha_t &\equiv \frac{L_t}{F_t} \cdot \frac{\partial F_t}{\partial L_t}, \quad \beta_t \equiv \frac{M_t}{F_t} \cdot \frac{\partial F_t}{\partial M_t}, \quad \pi_t = 1 - \alpha_t - \beta_t \end{aligned}$$

where “ $\wedge$ ” designates a growth rate and capital is assigned a residual output share. The measured Solow residual is then (in continuous time)

$$(4) \quad \hat{Z}_t \equiv \hat{Y}_t - \tilde{\alpha}_t \cdot \hat{L}_t - \tilde{\beta}_t \cdot \hat{M}_t - \tilde{\pi}_t \cdot \hat{K}_t = \hat{A}_t - \frac{d c_t}{d t}$$

where $\tilde{\alpha}$ and $\tilde{\beta}$ are estimates of the labor and materials elasticities, respectively. In discrete time,

these estimates are usually calculated as the average output share (average of the beginning and ending period), providing a Tornqvist index of productivity growth.

Equation (4) shows that the Solow residual growth, $\hat{Z}$, will be a biased estimator of true productivity growth if c changes over time. In “normal” circumstances where life proceeds smoothly along a balanced growth path, c might plausibly change little. However, when firms make radical shifts in technology, they may incur substantial new costs adopting that technology, biasing standard productivity measures.

Fortunately, equation (4) provides both a means to estimate c and, with estimates in hand, a means to adjust productivity measures.

Econometric Specification

Consider first the estimation of adjustment costs. To do this, I assign a functional form to c . In general, adjustment costs can be described as a function of the investment rate and technology, $c = c(I/K, T)$, where I is investment and T is some measure of technology. I will defer treatment of T until the next section, leaving just the investment relationship to be specified. After some experimentation, I chose

$$(5) \quad c_t = \gamma \cdot \frac{I_{t-1}}{K_{t-1}}$$

and several related forms. Then in discrete time, for the i th industry at time t (4) becomes

$$(6) \quad \hat{Z}_{it} = a_t + \mu_i - \gamma \cdot \Delta \left(\frac{I_{i,t-1}}{K_{i,t-1}} \right) + \varepsilon_{it}$$

where a represents overall productivity growth captured as a year dummy, μ represents an industry fixed effect, Δ is the first difference operator and ε is a stochastic error term. Note that the fixed effects capture fixed industry differences in the *rate* of productivity growth, such as differences that might arise from differences in R&D spending.

This equation is similar to one used by Lichtenberg [1988] in a study of plant level adjustment costs. My approach differs from his in several ways. I use a non-parametric measure of productivity growth as the dependent variable and I scale adjustment costs by the capital stock. Because I am comparing industries composed of different numbers of plants, it is necessary to scale investment by some measure of the capital stock. Like Lichtenberg, I use gross rather than

net investment. Lichtenberg, however, does go further and apportions his results between “replacement” investment and “expansion” investment.

Also, Lichtenberg uses current period investment while I use lagged investment. As Lichtenberg notes, simultaneity problems bias estimates of γ downward when current period investment is used. By using lagged investment, I avoid this simultaneity issue, although I potentially understate the total adjustment cost because I miss current period adjustment costs.

On the other hand, if productivity growth is serially correlated and the change in investment rate is correlated with productivity growth, last year’s simultaneity may also bias my estimates of γ . In general these correlations are not large: serial correlation of productivity growth is -.02 and +.14 for the NBER-CES and BLS samples (described below), respectively. The corresponding correlations between the change in investment rate and concurrent productivity growth are .11 and .04. So it is possible that the BLS estimates obtained using (6) may be biased toward zero. Performing a maximum likelihood AR1 estimation (not shown) generated similar coefficients and smaller standard errors. For the NBER-CES data, it is possible that some effect other than adjustment cost might cause the slight negative correlation, overstating estimates of γ . Tests of Granger causality (not shown) find that changes in the investment rate Granger-cause productivity growth in both data samples. Thus serial correlation issues do not appear to have much influence on the estimates obtained using (6).

Note also, that I assign a linear functional form to adjustment costs. This contrasts with much of the macroeconomic literature that assumes that adjustment costs are convex. My aim (like Lichtenberg’s) is to assess the magnitude of adjustment cost, not the curvature, so a linear form should be a reasonable first-order approximation to quadratic forms. In any case, experiments using quadratic specifications fit the data rather poorly and these specifications were rejected in favor of linear forms.

The linear specification does not capture fixed costs of adjustment either. However, episodes of zero investment occur in less than 0.1% of the sample. So fixed costs would be incurred in virtually all of my data, but the linear specification simply does not capture this effect. In other words, this specification will understate total adjustment costs if fixed costs occur. Note, also, that *external* adjustment costs are not captured.

The (undiscounted) average adjustment cost rate can be calculated using (5) and (1) as

$$(7) \quad \phi \equiv \frac{c \cdot Y^*}{I} = \gamma \cdot \frac{Y^*}{K_{t-1}}.$$

This represents the adjustment cost incurred by one dollar of investment. Given the linear specification, it also equals the marginal adjustment cost.

Measuring Productivity Growth

Equation (4) can be re-arranged

$$(8) \quad \hat{A}_t = \hat{Z}_t + \frac{dc_t}{dt},$$

indicating that true productivity growth may be obtained by adding dc/dt to the measured Solow residual.

This equation has a straightforward intuitive explanation. The adjustment cost represents a complementary investment that is not included in measured investment. But this unmeasured investment is a component of output. That is, Y^* is the measure of true output, which is larger than Y by the amount of investment, $c \cdot Y^*$. Then, using equation (1), $\hat{Y}^* = \hat{Y} + \frac{dc}{dt}$, or output grows faster by dc/dt .

I use equation (8) as a simple, basic means to correct measured productivity growth for adjustment cost changes. This assumes that all other inputs and outputs are measured correctly. This might not be the case, however, when adoption costs are large. There are two possible, offsetting effects: adoption costs may distort price deflators for capital goods and adoption costs may imply unmeasured capital stocks (human and/or physical capital). Some simple calculations suggest that the net effect of these measurement issues is probably not large (Bessen, 2002). I ignore them, and assume that other factors are measured correctly.

Finally, note that the role adjustment costs play above is counterpart to another well-recognized role they play in productivity growth accounting. Adjustment costs are commonly used to explain the effect of capacity utilization on productivity measurement. Capacity may not be fully utilized because “quasi-fixed” factors of production, such as capital, adjust only slowly to economic shocks. Assuming that firms optimize dynamically, a firm faced with a positive (negative) demand shock may not invest (disinvest) to the optimal long-run level because

investment incurs adjustment costs.³ But clearly, this can only be part of the story. If the *anticipation* of adjustment costs prevents firms from fully adjusting capacity, then when firms finally *do* invest, they must incur those adjustment costs. And this affects the measurement of productivity growth.

III. Empirical Results

Data and Variables

To estimate adjustment costs, I use a comprehensive, detailed panel of manufacturing industries that provides significant cross-sections and time series: the NBER-CES Manufacturing Industry Database [Bartelsman and Gray, 1996] from 1958 to 1996, which includes 459 industries at the 4-digit SIC code level (1987 SIC codes). I exclude asbestos products, SIC 3292, an industry that essentially disappeared in recent years due to legal restrictions.

I also use a smaller panel derived from the April, 2001 release of the BLS multifactor productivity database.⁴ This panel includes 19 2-digit SIC industries (I exclude tobacco), however, it also includes annual measures of IT investment and stocks, permitting investigation of the relationship between IT and adoption costs.

The variables used are described in the Appendix. However, two deserve further discussion. First, I experimented with several different specifications for the adjustment cost. As noted above, the investment measure needs to be scaled by a measure of industry size and I experimented with different scaling measures, including real output, total capital stock and structures stock. I obtained the best fit using investment divided by the stock of structures. This may occur because structures may be measured with less error than equipment. The results below, however, are based using investment divided by the total capital stock. The adjustment cost estimates are slightly lower, but the qualitative picture is quite similar.

Second, the capital stocks in the NBER-CES database were developed from industry level investment data using a perpetual inventory method.⁵ The specific methodology was developed at the Federal Reserve Board [Mohr and Gilbert, 1996] and uses BEA deflators (including the

³ See Dixit and Pindyck [1994] for an overview. See Berndt and Fuss [1986] for the specifics of correcting for capacity utilization in productivity growth accounting.

⁴ Thanks to Steve Rosenthal and Bill Gullickson for providing requested data.

⁵ These data only incorporate price deflators for computers from 1972 on. However, computers represent only a tiny fraction of capital in 1972, and even less for earlier years, so this should cause no significant bias.

hedonic deflator for computers), stochastic retirements, and beta decay of service efficiency. These stocks, like the BLS stocks, do not use the BEA depreciation rates that incorporate obsolescence along with physical depreciation.

To make sure this assumption was not critical, I developed a corresponding series of capital stocks using the current BEA methods [Katz and Herman, 1997, Fraumeni, 1997]. The adjustment cost estimates changed only slightly. I also derived estimates using the BLS data (Table 4 below). BLS estimates of productive capital stock weight detailed asset types differently (the NBER-CES data effectively only have 2 asset classes). The adjustment cost estimates obtained from the BLS data at the 2-digit level are reasonably close to the estimates from NBER-CES data at the 4-digit level.

Overall Measures

Table 1 presents several variations on equation (6). The first two columns show the regression with and without industry fixed effects.⁶ Industry fixed effects control for heterogeneity in industry-specific factors that might influence the average rate of productivity growth. For instance, industries with high R&D spending might experience faster productivity growth. If R&D were also correlated with investment, this might bias the estimates of adjustment costs. As shown there does not appear to be much bias; fixed effects are used in all subsequent regressions.

Columns 3 and 4 explore different lags in the investment term. The adjustment costs appear to diminish over time as would be expected. However, investment seems to incur statistically significant costs for up to two years, so I use adjustment terms with both one and two year lags (Column 5).

Following Berndt and Fuss [1986], I control for capacity utilization effects by assigning capital a residual share of output in the calculation of the Solow residual. However, this approach might not fully account for utilization effects if labor or materials do not adjust instantaneously. Capacity utilization might also affect estimates if returns to scale are not constant. I ran several additional regressions to correct for possible issues related to capacity utilization. Basu, Fernald, and Shapiro (2001) argue that the rate of utilization growth is proportional to the growth rate of hours worked per employee.⁷ In Column 6, I include this variable. It has a significant coefficient,

⁶ Durbin Watson tests do not indicate a problem with serial correlation.

⁷ Basu, Fernald and Shapiro (2001) present a model that includes both adjustment costs and capacity utilization for labor and capital. They argue that the major cost of increasing capital utilization is that firms have to pay a shift premium (higher wage) to compensate employees for working at night or at other undesirable times. In their model, without this cost, capital would be fully utilized.

but it does not appear to affect the estimates of adjustment costs. I also tried several other proxies for the rate of utilization, including the ratio of production wages to total wages and salaries. These regressions are not shown (see Bessen, 2002, and Bessen, 2003), but these other measures did not materially alter the adjustment cost estimates either.

To estimate the adjustment cost rate, ϕ , I use sample means and replace potential output with last year's actual output, $\gamma \cdot \bar{Y}_{t-1} / \bar{K}_{t-1}$. These estimates are shown in the bottom row.

For a single lagged value (Column 2), I find 17¢ of adjustment cost for each dollar of investment. By comparison, Lichtenberg, using plant level data also derived from the Census of Manufactures and Annual Survey of Manufactures, finds adjustment costs of 21¢ for replacement investment and 35¢ for expansion investment. Since the gross investment measure I use is the sum of replacement investment and expansion investment in Lichtenberg's study, my estimate based on industry aggregates is slightly lower than his. However, Lichtenberg uses only a single, current year of investment.⁸ When I include investment with a two-year lag, adjustment costs rise to 41¢ per dollar of investment. This is somewhat higher than Lichtenberg's estimates, however, considering the differences in method and data, these results are broadly consistent.

Incorrectly measured capital stocks might bias the estimates of adjustment cost. In particular, if the service efficiency of capital declines more rapidly than accounted for in the construction of the capital stock, a spurious negative correlation might arise, leading to biased estimates. Note that the capital stock in the NBER-CES database uses a beta decay model of service efficiency. This tends to decay less rapidly during the first few years after new capital is installed. BEA capital stocks, largely based on geometric depreciation, tend to decline more rapidly than beta decay during the early years of use. To examine the robustness of the estimates, I constructed a corresponding set of investment rates and capital stocks for each 4-digit industry using BEA methods and BEA depreciation. Regressions using these alternative stocks did not generate materially different estimates of adjustment costs (results not shown).

Given this assumption, they find that firms increase utilization across all margins at once. Specifically, they show that the rate of utilization growth is proportional to the growth rate of hours worked per employee. They then use the growth rate of hours as a proxy for utilization in regression equations. See also Basu, Fernald and Kimball (1999) and Basu and Kimball (1997).

⁸ Lichtenberg failed to obtain significant results using lagged investment in his specification. However, given the noisiness of plant level data, this is not surprising.

Time Trends

Table 2 presents the regression performed over different intervals. Table 2a shows 3 longer intervals and Table 2b shows each of these further divided into two shorter intervals. Figure 2 displays the adjustment costs from Table 2b.

A sharp and dramatic pattern emerges. Adjustment costs more than doubled from the early 60's to the late 70's and early 80's. This is a rather large difference. After 1988 the standard errors grow large and the coefficients lose significance. This change could arise from increased errors in measuring capital and investment. For instance, the NBER-CES data does not include spending on unbundled software which looms large in the new BEA and BLS accounts [Parker and Grimm, 2000]. Or it may mean that the new information systems used in different industries have very disparate effects on adjustment costs.

To explore the time pattern of adjustment costs more precisely, I also estimated a non-linear model assuming that the coefficients increased linearly from 1974 to a terminal year. After some experimentation, the best fit was achieved with 1986 as the terminal year. Then the following equation was estimated using non-linear least squares from 1961 through 1988:

$$\hat{Z} = \begin{matrix} .007 \\ (.001) \end{matrix} - \begin{pmatrix} .101 \\ (.019) \end{pmatrix} + \begin{pmatrix} .018 \\ (.004) \end{pmatrix} T \cdot \Delta \left(\frac{I_{i,t-1}}{K_{i,t-1}} \right) - \begin{pmatrix} .087 \\ (.018) \end{pmatrix} + \begin{pmatrix} .012 \\ (.004) \end{pmatrix} T \cdot \Delta \left(\frac{I_{i,t-2}}{K_{i,t-2}} \right)$$

$$(9) \quad T \equiv \begin{cases} 0, & t < 1974 \\ t - 1973 & 1973 < t < 1987 \\ 13 & 1986 < t \end{cases}$$

with standard errors in parentheses below the coefficients ($R^2 = .011$). To estimate c for each year, I use sample means for lagged values of I and K . This gives the average value of c for individual industries. Since the aggregate output of the manufacturing sector is less than the sum of outputs of the industries (because some industries produce intermediates), I multiply this figure times the sum of industry output divided by sector output (from the BLS). This yields a value of c for the entire sector, expressing adjustment costs as a percent of aggregate output. The annual values are shown in Figure 3. After a small, temporary rise in the 60's, c increases from 2.4% in 1973 to 6.5% in 1983 and 7.1% in 1986. Thus adjustment costs as a percent of output rose over 4%.

The overall pattern is exactly what one would expect if many industries experienced technology transitions during the 70's and early 80's. As more industries switched to new

technologies they would experience rising adoption costs during this period. Once most firms had made the transition, subsequent capital vintages based on the new technologies would not incur such large increases in adoption costs and might even experience decreases in these costs.

Of course, many other conditions changed during the 70's as well, so this is not the only possible explanation. An important question is whether the rise in adjustment costs is technology-specific or not. For example, information technology or new energy efficient technology could incur specific learning costs. On the other hand, other sorts of changes might increase adjustment costs for all types of investments, giving rise to non-technology-specific increases in adjustment costs. This might be the case if, say, the educational quality of the workforce fell, making learning more costly. This might also be the case if government regulation made the installation of new equipment more costly.

Given the large size of the additional adjustment costs, it is difficult to identify a plausible non-technology-specific explanation. The labor force actually became more highly educated during the 70's. And although government pollution controls may have increased the installation costs of many types of equipment, it is hard to see how such increases could account for 4% of output. Moreover, most of this increase would be in the cost of the equipment itself, not in adjustment costs.

The 70's also saw an increase in R&D spending and rising energy costs. Both of these factors are likely to give rise to technology-specific adjustment costs—R&D generates new technology that may have adoption costs; shifts to energy efficient equipment may incur technology-specific adaptation costs. To explore these factors further, Table 3 repeats the regressions for different industry groups from 1970 – 83. Column 1 repeats the overall regression, and Columns 2 and 3 show the sample segregated into high tech and low tech industries. I identified 137 high tech industries which had high employment of scientists and engineers relative to total employment [Hadlock et al, 1991]. As can be seen, the high tech industries had somewhat higher adjustment costs, although the difference in coefficients is not quite significant at the 1% level. Columns 4 and 5 segregate the sample into high- and low-energy-using industries based on the ratio of energy consumption to output in 1970. Here, too, there is a modest, and not statistically significant, difference in favor of energy-intensive industries. Thus neither R&D nor a switch to energy efficient equipment appears to explain the sharp rise in adjustment costs, although they may contribute marginally.

IT and Adjustment Costs

It remains to explore the rise in IT spending as a possible cause of the rise in adjustment costs. To do this, I use the BLS panel, which includes IT investment.

First, it is necessary to check that this panel has adjustment patterns similar to those in the NBER-CES data, despite the reduced variation in the cross-sectional dimension. Column 1 of Table 4 performs a basic adjustment cost regression using a single lagged investment rate. Adding an additional lag did not generate a significant coefficient. For the single lag, the coefficient is highly significant and corresponds to an adjustment cost of 57¢ per dollar of investment, somewhat higher than the 41¢ in Table 1, but reasonably similar given the differences in data and capital measures.

Column 2 tests whether adjustment costs rose sharply in the BLS panel from 1974-83. I add a variable that is zero outside of this interval and equals the change in the investment rate during this interval. The coefficient should reflect the increment in adjustment costs during this period. Although the coefficient is only significant at the 5% level, it is roughly the right magnitude and reflects a large increase in adjustment costs. Combined, the coefficients imply an adjustment cost of 94¢ from 1974-83 and of 41¢ before and after this interval. Again, these figures are somewhat higher than in Table 2a, but reasonably similar. Thus the basic pattern observed in the much larger NBER-CES database also appears here.

To test for a link between IT spending and adjustment costs, I modify the specification of adjustment costs in (5) to include a proxy for information technology. The basic intuition is that a higher share of IT in investment or in the capital stock might incur higher adjustment costs. Two simple specifications are

$$(10) \quad c_t = \gamma \cdot \frac{I_{t-1}}{K_{t-1}} + \delta \cdot \frac{I_t^{IT}}{I_t} \quad \text{and} \quad c_t = \gamma \cdot \frac{I_{t-1}}{K_{t-1}} + \delta \cdot \frac{K_{t-1}^{IT}}{K_{t-1}}$$

where I^{IT} and K^{IT} are real IT investment and stock, respectively. The capital share in second specification may be thought of as a proxy for relative investment flows over several years. With these specifications, any increase in IT-intensity incurs a temporary reduction in measured productivity growth.

Columns 3 and 4 use the first of these specifications, without and with time dummies. After some experimentation, I found that the regression fit best with zero lag in the IT term, and so this is what I present in these regressions, despite the possible attenuation of the coefficient because of simultaneity issues. The IT coefficient is highly significant in Column 3, but when time dummies

are added, the significance disappears. The independent variation in the cross-sectional dimension of IT investment may simply be insufficient to offset the simultaneity losses.

Column 5 uses the stock specification. This is less volatile and can be used well with a lag. Here the results with time dummies are highly significant and with a large coefficient for IT share of capital. Comin (2002) has questioned whether this negative association between the IT share of capital and productivity growth is persistent, or, instead, whether it might only apply during the 60's. A series of statistical tests (Bessen 2003) reject the hypothesis that this coefficient fell to zero after the 60's and fail to reject the hypothesis that the coefficient did not change throughout the entire sample period. Thus there does appear to be a strong and persistent link between the IT share and a loss of productivity.

But does this account for the rise in adjustment costs measured in Table 2? Using (7) applied to the specification in Column 5 at mean sample values, I calculated the mean adjustment cost per dollar of investment for the intervals in Table 2a. From 1961-73 the calculated mean adjustment cost is 37¢, from 1974-83 it is 72¢, and from 1984-96 it is \$1.68. Estimates for the first two intervals match rather closely. Increased IT spending does seem to account for the sharp increase in adjustment costs in the 70's and early 80's. However, after 1984, the estimates diverge. Recall, however, that the estimates for the last interval in Table 2a have large standard errors and are not statistically significant, possibly because the NBER-CES data may not fully capture IT investment. So this divergence is not necessarily at odds with a link between adjustment costs and IT.

To test whether the linear specification of IT share in Column 5 might cause adjustment cost estimates in the 90's to be overstated, I added a quadratic term in Column 6. These estimates do suggest a slight concavity, but the coefficients are not significant and even then, the estimated concavity is relatively slight.

Finally, I use the estimates in Column 5 to calculate annual values of c using sample means. These are also shown in Figure 3 for 1961 through 1988. As can be seen, these estimates are quite similar to the estimates obtained using NBER-CES detailed industry data, although they tend to run slightly higher. Thus the two estimates generate a consistent pattern of adjustment costs, one based on IT and total investment, the other just using investment data.

Based on this evidence, I conclude that the sharp rise in adjustment costs during the 70's and early 80's can be plausibly attributed to increased IT investment. Greater R&D and a

transition to energy efficient equipment may have also contributed to a lesser degree. In other words, adjustment costs rose because of technology adoption costs.

IV. Implications for Productivity Growth Measurement

Adjustments to BLS Estimates for Manufacturing

The estimates above can be used to adjust official estimates of manufacturing sector productivity growth using equation (8). There are two steps to this process. The first step is to obtain annual estimates for these variables so that dc/dt can be calculated for each industry. The second step aggregates this adjustment over the entire manufacturing sector.

I use two different methods to calculate dc/dt . One uses the coefficients of equation (9) for the NBER-CES data. This equation implicitly fits g_t to a piecewise linear curve,

$$(11) \quad \gamma_t = \alpha_0 + \alpha_1 T, \quad T = \begin{cases} 0, & t < 1974 \\ t - 1973, & 1973 < t < 1987 \\ 13, & 1986 < t \end{cases}.$$

I used the coefficients from this regression to estimate dc/dt using

$$(12) \quad \frac{dc_t}{dt} = \gamma_t \frac{d}{dt} \left(\frac{I_{t-1}}{K_{t-1}} \right) + \frac{I_{t-1}}{K_{t-1}} \cdot \frac{d\gamma_t}{dt} \approx \gamma_t \Delta \left(\frac{I_{t-1}}{K_{t-1}} \right) + \frac{I_{t-1}}{K_{t-1}} \cdot \Delta \gamma_t.$$

The second method uses the coefficients from the regression in Column 5, Table 4 to estimate dc/dt for the BLS data. This method assumes that

$$(13) \quad \frac{dc_t}{dt} \approx \gamma \cdot \Delta \frac{I_{t-1}}{K_{t-1}} + \delta \cdot \Delta \frac{K_{t-1}^{IT}}{K_{t-1}},$$

following from (10). In words, this method assumes that the change in the IT share of capital proxies for $\Delta\gamma$.

These estimates of dc/dt provide adjustments to the productivity of individual industries. I wish to adjust the BLS estimates for the entire manufacturing sector, so these must be aggregated. Since the BLS output index is calculated as an annual chain-weighted Tornqvist index of industry deflated net output (net of intra-sector transactions), I create a similarly weighted index for the adjustments. The details of this procedure are described in Bessen (2003).

The first row of Table 5 displays the annualized productivity estimates from the BLS April 2001 release broken into four periods. As can be seen, these measures exhibit the well-known

“productivity slowdown.” Productivity growth during 1974-88 fell to 1.13% per annum compared to 1.52% during 1949-73.⁹ Using shorter intervals, growth fell to 0.52% from 1974-83 compared to 1.84% from 1961-73.

The following two rows show the average annual growth in c and the adjusted productivity growth estimates using the NBER-CES estimates from (9). The last two rows show comparable estimates using BLS data with the specification in Column 5 of Table 4. The adjustments have a substantial impact. A productivity slowdown still appears comparing the shorter intervals, but comparison of the longer intervals suggests either a small slowdown or, possibly even a small productivity growth increase.

As noted above, these productivity growth estimates ignore possible measurement problems associated with adoption costs. They also assume either a particular functional form for the growth in adjustment costs (for the NBER-CES sample) or a relationship between the IT share of capital and adjustment costs (for the BLS sample). Nevertheless, these results demonstrate that adoption costs during technology transitions can easily introduce very large errors into standard productivity calculations. And the interpretation of technical change during the 70’s lies in the balance.

V. Conclusion

Moses Abramowitz [1956] called the Solow residual a “some sort of measure of ignorance.” It is, perhaps, comforting to assume that our ignorance grows only gradually and that the rate of technological change remains more or less constant. But evidence from history and evidence on the “diffusion” of innovations suggest that technologies frequently exhibit dramatic, Schumpeterian transitions.

This paper finds evidence of just such a transition during the 1970’s: the cost of installing and implementing new capital more than doubled. And I find evidence linking this increase to a greater share of investment in IT. Such a dramatic change suggests that firms experienced large adoption costs when switching to new technologies. This concurs with case study evidence.

But a rapid increase in adoption costs implies that the Solow residual does not accurately measure productivity growth. Calculations based on estimated adoption costs demonstrate that productivity growth may have substantially exceeded the Solow residual during the 70’s, shrinking

⁹ A business cycle trough (NBER) occurred during 1949 and a peak in 1973. In 1974 the economy was in recession, but the official trough was reached in 1975.

the measure of the productivity slowdown. In other words, much of the apparent productivity slowdown may be an artifact of measurement error. Our ignorance may, in fact, increase sharply during periods of technological transition.

This is important because, from a longer historical perspective, technology transitions may not be infrequent. The shift to an increasing share of investment going to information technology is, in fact, part of a longer secular trend—the share of investment going to equipment has increased overall (with occasional interruptions) since the nineteenth century. Some of this increase can be readily identified with new technologies, e.g., the growth in spending on electrical devices and electric transmission equipment during the middle of the last century.

From this perspective, the 60's—when measured productivity was high, but also when the equipment share of investment did not increase—may have been a temporary respite from the technology transitions implied by this trend. Rather than a “normal” period, this era may have benefited from improvements to existing technologies without the costs of adopting many new technologies.

The rise in adoption costs during a technology transition affects more than productivity growth. Other researchers have argued that adoption costs may also relate to changes in wage inequality, wage skill premia, the relative employment of skilled workers, and stock prices [Hornstein and Krusell, 1996, Greenwood and Yorukoglu, 1997, and Greenwood and Jovanovic, 1998]. The results here emphasize the importance of these connections.

Appendix.

Definitions of Variables used in the NBER-CES Estimations

L	Labor calculated as annual production hours times the ratio of total payroll to production wages. This includes non-production labor in efficiency units.
M	Deflated materials and energy.
K	Real net capital stock based on FRB methods. Stocks of individual asset types are calculated using stochastic service lives and beta decay of efficiency. Depreciation does not include obsolescence. Stocks of different asset types are added one-for-one to compose aggregate stock.
Y	Real output calculated as deflated shipments plus inventory change.
I / K	Investment rate calculated as deflated gross investment divided by net real plant.
α	Labor share of output calculated as total payroll divided by nominal shipments plus inventory change. This quantity is then multiplied by the ratio of employee compensation to wages and salaries found in the NIPA tables for the corresponding 2-digit SIC industry and year.
β	Materials share calculated as nominal cost of materials and energy divided by nominal shipments plus inventory change.
π	Capital share of output calculated as $1 - \alpha - \beta$ (assumes constant returns to scale)

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Table 1. Adjustment Cost Regressions, All Industries, NBER-CES data, 1961 - 1996
 Dependent variable: productivity residual growth

Variable	1	2	3	4	5	6
$\Delta(I/K)_{t-1}$	-.070 (.030)	-.075 (.030)			-.105 (.036)	-.105 (.036)
$\Delta(I/K)_{t-2}$			-.047 (.017)		-.081 (.019)	-.080 (.019)
$\Delta(I/K)_{t-3}$				-.011 (.016)		
$\pi \cdot \Delta(\text{production hrs/employee})$						-.084 (.039)
year dummies	✓	✓	✓	✓	✓	✓
industry dummies		✓	✓	✓	✓	✓
Adjusted R-squared	.068	.092	.091	.091	.094	.095
Adjustment cost rate	.15	.17	.10	.02	.41	.41

Notes: 458 industries x 36 years = 16,488 observations. Differences are over one year. Robust standard errors in parentheses. Adjustment rates estimated at sample means. π is capital share of output calculated as one minus labor share of output minus materials share of output.

Table 2a. Adjustment Cost Regressions By Period, Long Intervals
 Dependent variable: productivity residual growth

Variable	1961-73	1974-83	1984-96
$\Delta(I/K)_{t-1}$	-.095 (.020)	-.189 (.041)	-.088 (.104)
$\Delta(I/K)_{t-2}$	-.057 (.018)	-.184 (.037)	-.063 (.049)
Number of observations	5,954	4,580	5,954
Adjusted R-squared	.090	.114	.058
Adjustment cost rate	.35	.79	.32

Table 2b. Adjustment Cost Regressions By Period, Short Intervals
 Dependent variable: productivity residual growth

Variable	1961 - 68	1969 - 73	1974 - 78	1979 - 83	1984 - 88	1989 - 96
$\Delta(I/K)_{t-1}$	-.084 (.023)	-.147 (.042)	-.149 (.057)	-.256 (.064)	-.265 (.083)	-.061 (.121)
$\Delta(I/K)_{t-2}$	-.056 (.021)	-.076 (.038)	-.251 (.053)	-.093 (.061)	-.186 (.104)	-.035 (.056)
Number of observations	3,664	2,290	2,290	2,290	2,290	3,664
Adjusted R-squared	.067	.068	.116	.059	-.018	.050
Adjustment cost rate	.33	.51	.88	.72	.90	.21

Notes: NBER-CES data for 458 total industries. All regressions include industry and year dummies. Differences are over one year. Robust standard errors in parentheses. Adjustment costs estimated at sample means.

Table 3. Adjustment Cost Regressions, Industry Groups, NBER-CES data, 1970 - 83
 Dependent variable: productivity residual growth

	All Industries	High tech	Low tech	High energy use	Low energy use
Variable	1	2	3	4	5
$\Delta(I/K)_{t-1}$	-.175 (.032)	-.225 (.057)	-.156 (.038)	-.179 (.044)	-.172 (.046)
$\Delta(I/K)_{t-2}$	-.157 (.028)	-.138 (.056)	-.156 (.032)	-.198 (.039)	-.120 (.041)
Number of observations	6,412	1,918	4,494	3,206	3,206
Adjusted R-squared	.108	.210	.052	.079	.133
Adjustment cost rate	.73	.79	.68	.82	.64

Notes: 458 total industries. All regressions include industry and year dummies. Differences are over one year. Robust standard errors in parentheses. Adjustment costs estimated at sample means.

Table 4. Adjustment Cost Regressions, BLS Data, 1960 - 1996

Dependent variable: multi-factor productivity growth

Variable	1	2	3	4	5	6
$\Delta(I/K)_{t-1}$	-.54 (.11)	-.39 (.13)	-.53 (.11)	-.30 (.12)	-.29 (.12)	-.28 (.12)
$\Delta(I/K)_{t-1}$ & $(73 < t < 84)$		-.50 (.25)				
$\Delta(I^{\text{IT}}/I)_t$			-.24 (.07)	-.11 (.08)		
$\Delta(K^{\text{IT}}/K)_{t-1}$					-1.68 (.49)	-2.17 (.87)
$\Delta(K^{\text{IT}}/K)_{t-1}^2$						3.33 (4.86)
year dummies				✓	✓	✓
industry dummies	✓	✓	✓	✓	✓	✓
Adjusted R-squared	.092	.096	.106	.249	.260	.259

Notes: 19 industries x 37 years = 703 observations (excludes tobacco). Differences are over one year. Robust standard errors in parentheses. IT investment and productive capital stock includes software and computer, communications and other hardware. Source: BLS, April, 2001 release.

Table 5. Productivity Growth Calculations
 Annualized growth rates for the manufacturing sector.

	1949 - 73	1974 - 88	1961 - 73	1974 - 83
$\hat{Z}$ - BLS MFP growth	1.52%	1.13%	1.84%	0.52%
<u>Adjustment costs from NBER-CES data</u>				
dc/dt	--	0.32%	-0.01%	0.46%
Adjusted productivity growth, $\hat{Z} + dc/dt$	--	1.45%	1.83%	0.98%
<u>Adjustment costs from BLS data</u>				
dc/dt	--	0.63%	0.11%	0.62%
Adjusted productivity growth, $\hat{Z} + dc/dt$	--	1.76%	1.95%	1.14%

Sources: BLS April, 2001 release. Adjustment cost series described in the text.

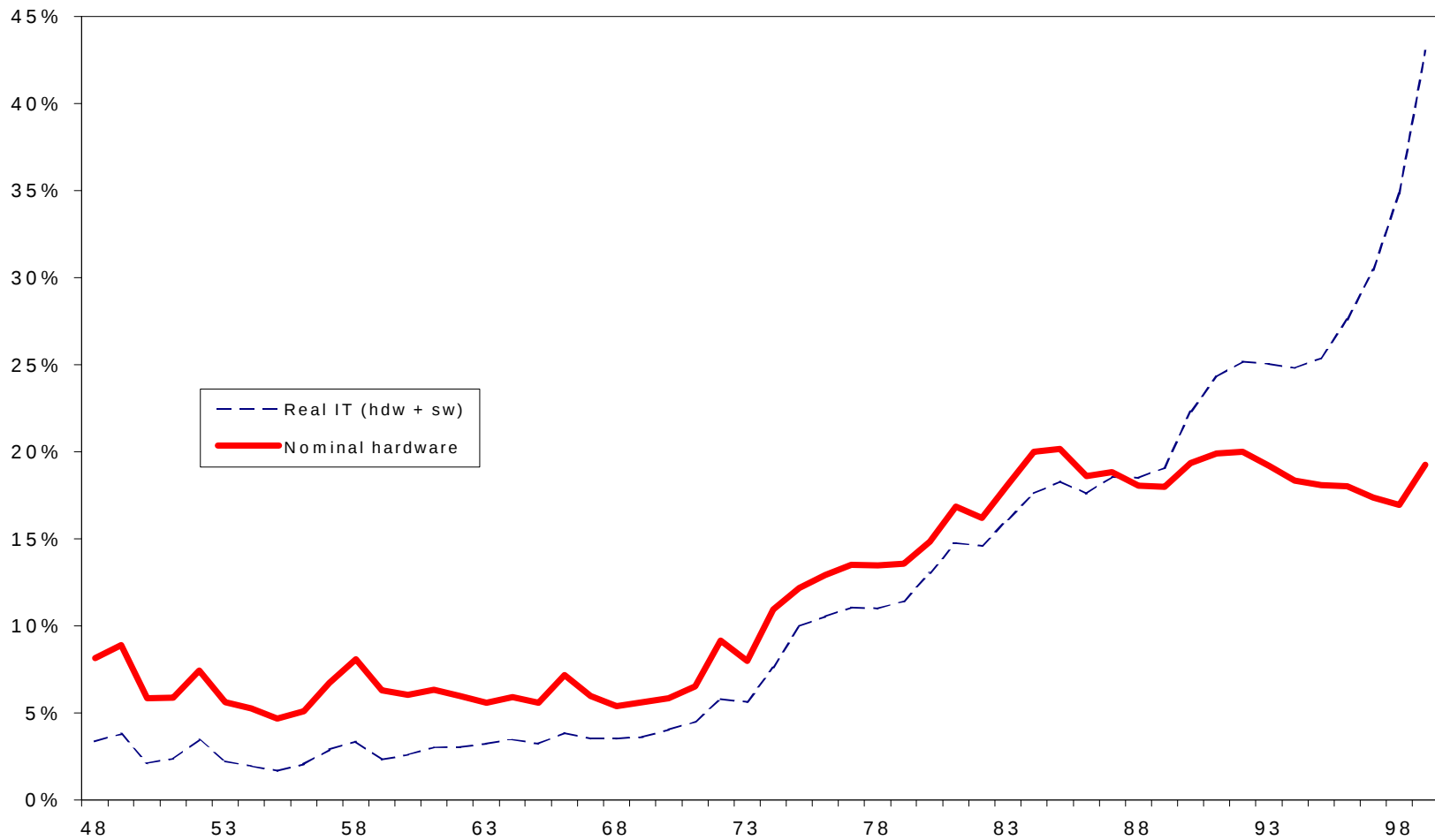


Figure 1. Share of Manufacturing Investment going to IT.

Source: BLS, April, 2001 Manufacturing and 2-Digit Multifactor Productivity Data

Total IT includes hardware and software; hardware includes computer equipment, communications and other equipment.

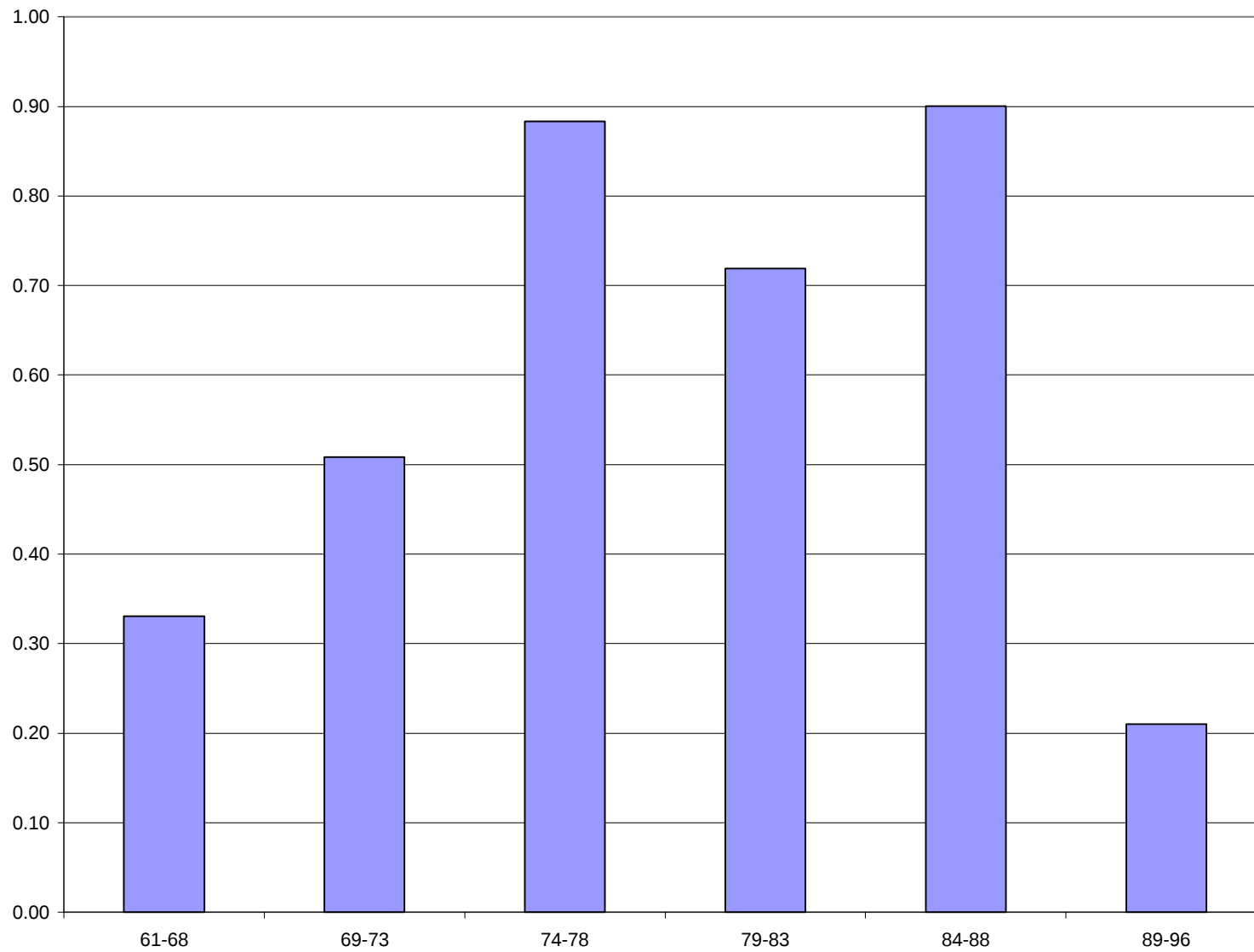


Figure 2. Adjustment Costs per Dollar Investment.
Source: Table 2b.

Figure 3. Adjustment Costs as a Percentage of Manufacturing Sector Output.

