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LONG-RUN IMPLICATIONS OF INVESTMENT-SPECIFIC TECHNOLOGICAL CHANGE

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January 1995 (Revised)

Abstract

The role that investment-specific technological change played in generating postwar U.S. growth is investigated here. The premise is that the introduction of new, more efficient capital goods is an important source of productivity change, and an attempt is made to disentangle its effects from the more traditional Hicks-neutral form of technological progress. The balanced-growth path for the model is characterized and calibrated to U.S. National Income and Product Account data. The quantitative analysis suggests that investment-specific change accounts for the major part of growth.

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1 Introduction

The price and quantity series for equipment investment in the postwar U.S. display two striking features:

- Low frequency: The relative price of equipment has declined at an average annual rate of more than 3%. Simultaneously, the equipment-to-GNP ratio has increased substantially. Both patterns, which are fairly dramatic, are portrayed in Figures 1.

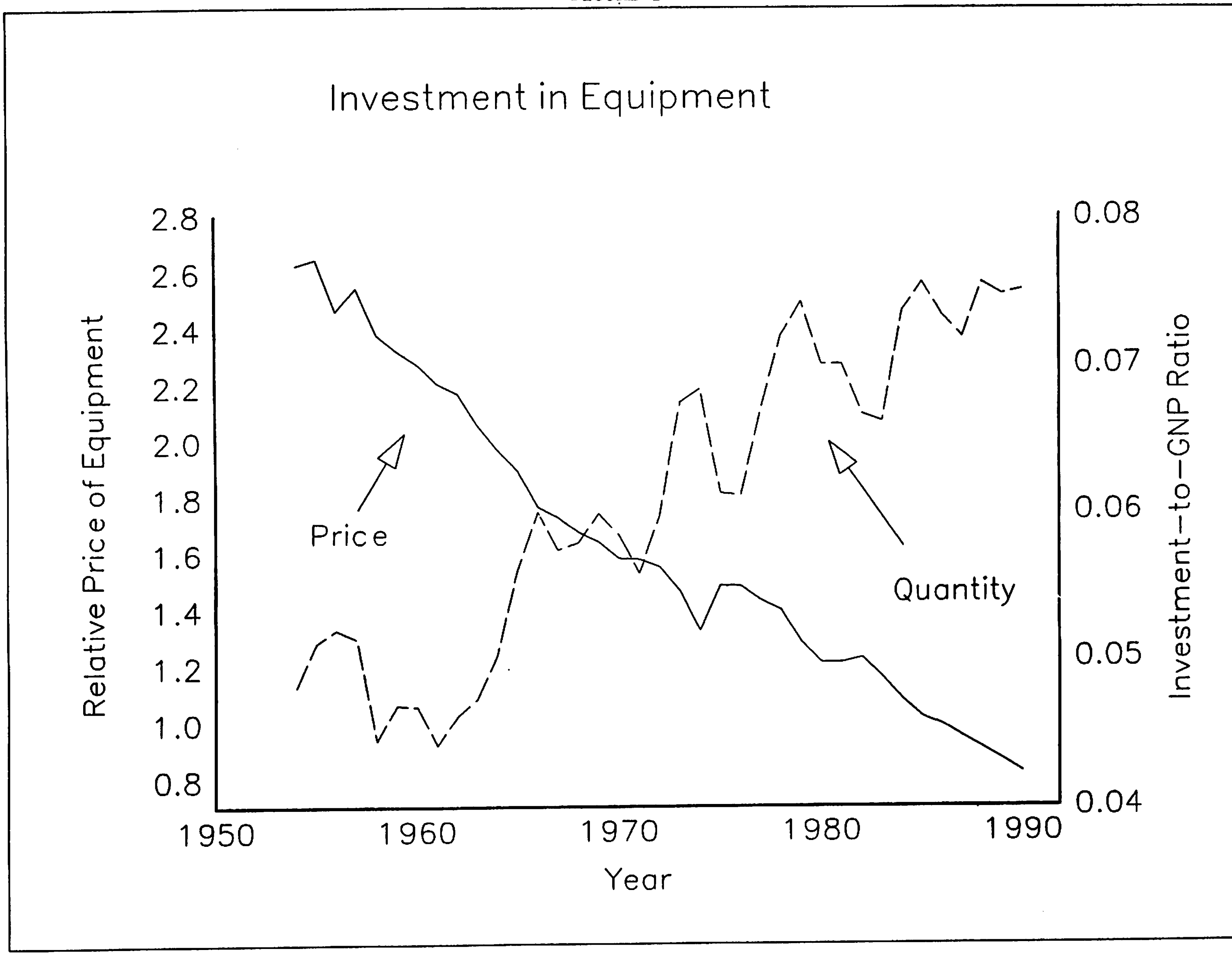
- High frequency: There is a negative correlation (-0.46) between the detrended relative price of new equipment and new equipment investment. This is shown in Figure 2.[1]

The negative comovement between price and quantity at both frequencies can be interpreted as evidence that there has been significant technological change in the production of new equipment. Technological advances have made equipment less expensive, triggering increases in the accumulation of equipment both in the short and long run. Concrete examples in support of this interpretation abound: new and more powerful computers, faster and more efficient means of telecommunication and transportation, robotization of assembly lines, and so on.

These observations bring to fore the following question: What is the quantitative role of investment-specific technological change as an engine of growth? To address this question, a simple vintage capital model is embedded into a general equilibrium framework. The main feature of the model is that the production of capital goods becomes increasingly efficient with the passage of time. By analyzing the balanced-growth path for the model, the contribution of investment-specific technological change to U.S. postwar economic growth is gauged. The balanced-growth path for the model has the feature that both the stock of equipment and new equipment investment (measured in quality-adjusted units) grow at a higher rate than output. The upshot of the analysis is that investment-specific technological

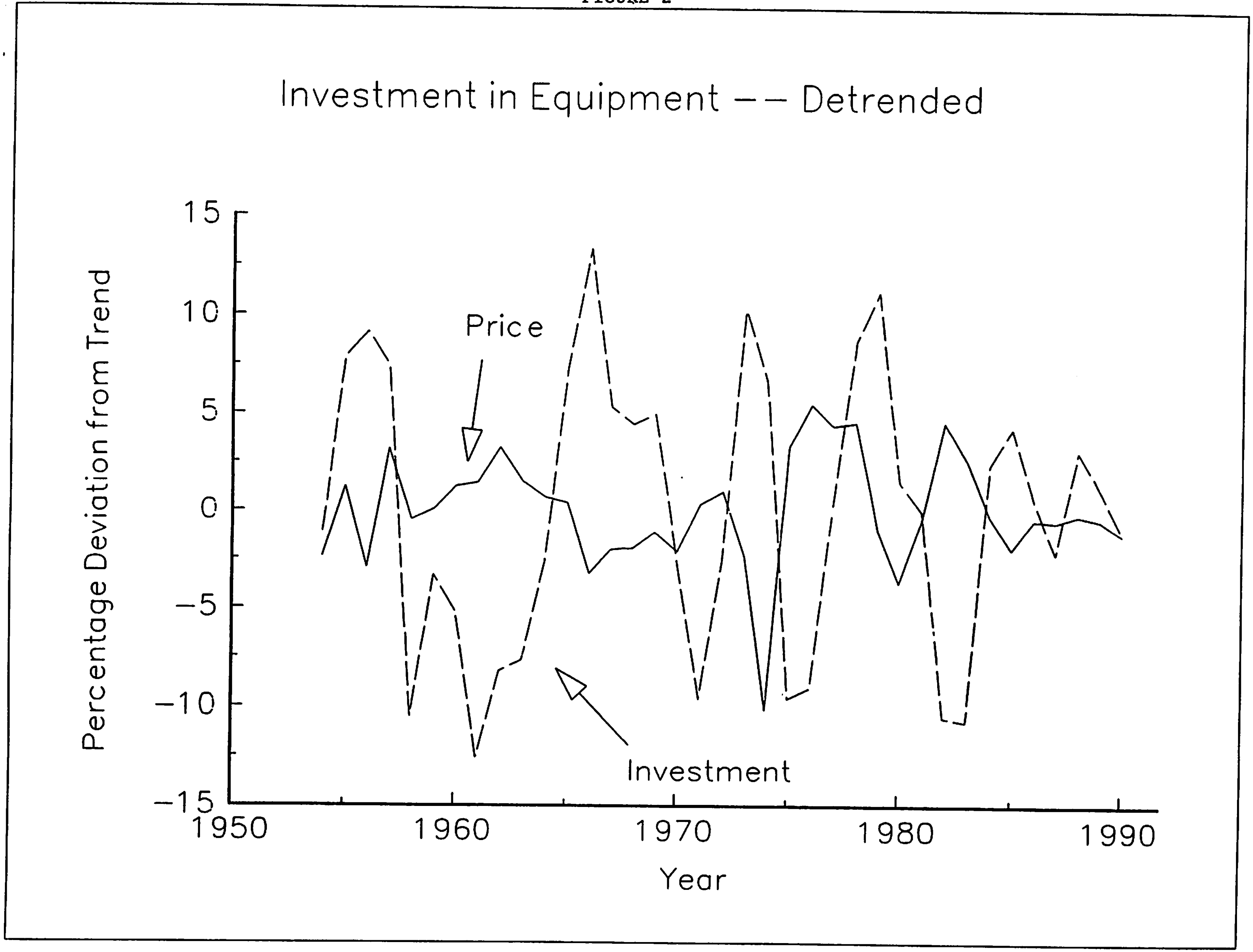
[1] For the quantity series standard National Income and Product Account data is used. The price series are based on data in Gordon (1990). See Appendix A for more detail on the data series.

FIGURE 1



Investment in Equipment
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
Relative Price of Equipment
0.08
0.07
0.06
0.05
0.04
Investment-to-GNP Ratio
Price
Quantity
1950
1960
1970
1980
1990
Year

FIGURE 2


Investment in Equipment -- Detrended
Percentage Deviation from Trend
15
10
5
0
−5
−10
−15
Price
Investment
1950
1960
1970
1980
1990
Year

change explains close to 60% of the growth in output per hours worked. Residual, neutral productivity change then accounts for the remaining 40%. Additionally, a striking result from this growth accounting exercise is that the time series for residual productivity change has regressed sharply and continuously since the early 1970's. The conclusion from this exercise seems to be that once capital quality is taken into account, the much-discussed productivity slowdown becomes all the more dramatic.[2]

The current study is a related to Hulten (1992), which also stresses capital-embodied technological change as key to long-run productivity movements. Both works use Gordon's (1990) price index, which was constructed precisely to capture the increased efficiency content in new capital goods. A key distinction between the two papers, however, is the adoption of a general equilibrium approach here. In line with conventional growth accounting, Hulten (1992) uses an aggregate production function to decompose output growth into technological change and changes in inputs, in particular capital accumulation. Clearly, though, a large part of capital stock growth reflects the endogenous response of capital accumulation to technological change. By taking a general equilibrium approach, the current analysis can go one step further: inferences can be made about how much of capital stock growth was due to investment-specific technological change versus neutral productivity growth. The point that part of observed growth in capital is the result of technological change, and that growth accounting procedures should adjust for this, has also been recognized in work by Hulten (1979).

Additionally, as highlighted by Hulten (1992), there is a controversy in the growth accounting literature over whether or not GNP should be adjusted upwards to reflect quality improvements in the new capital goods. The general equilibrium approach taken here provides a decisive answer to this question: it should not be. This finding is important since the quality adjustment significantly reduces the role ascribed to investment-specific, as opposed to neutral, productivity change in explaining U.S. output growth.

2 The role that investment-specific technological change plays in generating business cycle fluctuations is addressed in Greenwood, Hercowitz and Krusell (1994).

The paper is organized as follows: Section 2 presents the model and provides a characterization of its balanced-growth path. The model is calibrated to the National Income and Products Accounts (NIPA) in Section 3. The contribution of investment-specific technological change to postwar U.S. economic growth is then assessed. Section 4 compares the current analysis with conventional growth accounting. Based on the findings, some potentially interesting avenues for future empirical research on growth are suggested in Section 5. In particular, some ways of endogenizing investment-specific technological change are discussed. Finally, in Section 6 some concluding remarks are made.

2 The Model

2.1 The Economic Environment

Consider an economy inhabited by a representative agent who maximizes the expected value of his lifetime utility as given by

$$E[\sum_{t=0}^{\infty} \beta^t U(c_t, l_t)], \tag{1}$$

with

$$U(c,l) = \theta \ln c + (1-\theta)\ln(1-l), \quad 0 < \theta < 1, \tag{2}$$

where c and l represent consumption and labor.[3]

The production of final output y requires the services of labor, l, and two types of capital: equipment, k_e, and structures, k_s. Production is undertaken in accordance with

$$y = zF(k_e, k_s, l) = z k_e^{\alpha_e} k_s^{\alpha_s} l^{1-\alpha_e-\alpha_s}, \quad 0 < \alpha_e, \alpha_s < 1. \tag{3}$$

The variable z is a measure of total-factor, or neutral, productivity. Final output can be used for three purposes: consumption, c, investment in structures, i_s, and investment in equipment, i_e:

$$y = c + i_e + i_s. \tag{4}$$

3

Time subscripts are omitted whenever there is no risk of ambiguity.

Note that the theoretical constructs are normalized so that both output and investment are measured in units of consumption.

Structures can be produced from final output on a one-to-one basis. The stock of structures evolves according to

$$k_s' = (1 - \delta_s)k_s + i_s, \text{ where } 0 < \delta_s < 1. \tag{5}$$

The story is different for equipment. The accumulation equation for equipment is expressed as

$$k_e' = (1 - \delta_e)k_e + i_e q. \tag{6}$$

The most important aspect of this equation is the inclusion of the factor q that represents the current state of the technology for producing equipment. It determines the amount of equipment, as measured in efficiency units, that can be purchased for one unit of output. Changes in q formalize the notion of investment-specific technological change. Assume that both q and z follow first-order Markov processes that display average growth rates of γ_q and γ_z, respectively. Observe that investment-specific technological change is assumed to affect equipment only. The motivation for this is empirical. First, the relative price of structures appears to be stationary over time in the U.S. data, as does the structures-to-GNP ratio. Second, casual observation suggests that there is less productivity change in structures than in equipment.

Finally, there is also a government present in the economy. It levies taxes on the market income earned by labor and capital at the rates τ_l and τ_k. The revenue raised by the government in each period is rebated back to agents in the form of lump-sum transfer payments in the amount τ. The government's budget constraint is

$$\tau = \tau_k(r_e k_e + r_s k_s) + \tau_l w l, \tag{7}$$

where r_e, r_s and w represent the market returns for the services equipment, structures and labor. The inclusion of income taxation in the framework is important for the quantitative analysis because of the significant effect that it has on equilibrium capital formation.

Notice that movements in q can be interpreted in two different ways. First, one could imagine that in each period a new generation of machines is produced. The efficiency level of a new machine is given by q, where q increases over time, whereas the cost of producing a new machine is fixed over time at one unit of final output. Consequently, the cost per efficiency unit of machine declines secularly. This is often labeled capital-embodied technological change. Alternatively, one could assume that the efficiency level of a unit of new equipment remains constant over time. Now, $1/q$ could be thought of as representing the cost of this producing this machine in terms of final output. This cost declines secularly. Again, the cost per efficiency unit of new machines will fall over time. What both these forms of technological change have in common is that they are specific to the production of investment goods, which is why the term *investment-specific* is chosen here. Note, hence, that investment-specific technological change requires investment in order to affect output, whereas neutral technological change does not.

A key variable in the model is the equilibrium price for an efficiency unit of newly-produced equipment, using consumption goods as the numéraire. In the framework developed, this price corresponds on the one hand to the inverse of the investment-specific technology shock, q. On the other, it is the direct theoretical counterpart to a relative price series for new equipment that is computed using a price index for quality-adjusted equipment constructed by Gordon (1990).[4] Hence, investment-specific technological change can be identified here with a relative price index based on Gordon's price series.

2.2 Competitive Equilibrium

The competitive equilibrium under study will now be formulated. The aggregate state of the world is described by $\lambda = (s, z, q)$, where $s \equiv (k_e, k_s)$. Assume that the equilibrium wage and rental rates w, r_e and r_s, and individual transfer payments τ can all be expressed as functions of the state of the world λ as follows: $w = W(\lambda)$, $r_e = R_e(\lambda)$, $r_s = R_s(\lambda)$, $\tau = T(\lambda)$. Finally, suppose that the two capital stocks evolve according to $k_e' = K_e(\lambda)$ and $k_s' = K_s(\lambda)$.

4

See Appendix A for a more detailed discussion on this.

Hence, the law of motion for s is $s' = S(\lambda) \equiv (K_e(\lambda), K_s(\lambda))$. The optimization problems facing households and firms can now be cast. Of course, all agents take the evolution of s, as governed by $s' = S(s, z, q)$, to be exogenously given.

2.2.1 The Household

The dynamic program problem facing the representative household is

$$V(k_e, k_s; s, z, q) = \max_{c, k_e', k_s', l} \{U(c, l) + \beta \; E[V(k_e', k_s'; s', z', q')]\} \qquad P(1)$$

subject to

$$\begin{aligned} c + k_e'/q + k_s' &= (1-\tau_k)[R_e(\lambda)k_e + R_s(\lambda)k_s] + (1-\tau_l)W(\lambda)l \\ &\quad +(1-\delta_e)k_e/q + (1-\delta_s)k_s + T(\lambda) \end{aligned}$$

and $s' = S(\lambda)$.

2.2.2 The Firm

The maximization problem of the firm is

$$\max_{k_e, k_s, l} \pi_y = zF(k_e, k_s, l) - R_e(\lambda)k_e - R_s(\lambda)k_s - W(\lambda)l. \qquad P(2)$$

Due to the constant-returns-to-scale assumption, the firm makes zero profits in each period; i.e., $\pi_y = 0$.

2.2.3 Definition of Equilibrium

A competitive equilibrium is a set of allocation rules $c = C(\lambda)$, $k_e' = K_e(\lambda)$, $k_s' = K_s(\lambda)$, and $l = L(\lambda)$, a set of pricing and transfer functions $w = W(\lambda)$, $r_e = R_e(\lambda)$, $r_s = R_s(\lambda)$, and $\tau = T(\lambda)$, and an aggregate law of motion for the capital stocks $s' = S(\lambda)$, such that

1. Households solve problem (P1), taking as given the aggregate state of the world $\lambda = (s, z, q)$ and the form of the functions $W(\cdot)$, $R_e(\cdot)$, $R_s(\cdot)$, $T(\cdot)$ and $S(\cdot)$, with the

equilibrium solution to this problem satisfying $c = C(\lambda)$, $k_e' = K_e(\lambda)$, $k_s' = K(\lambda)$, and $l = L(\lambda)$.

2. Firms solve the problem (P2), given λ and the functions $R_e(\cdot)$, $R_s(\cdot)$, and $W(\cdot)$, with the equilibrium solution to this problem satisfying $\tilde{k}_e = k_e$, $\tilde{k}_s = k_s$ and $l = L(\lambda)$.

3. The economy-wide resource constraint (4) holds each period so that

$$c + i_e + i_s = zF(k_e, k_s, l),$$

where

$$i_s = k_s' - (1 - \delta_s)k_s,$$

and

$$i_e = [k_e' - (1 - \delta_e)k_e]/q,$$

2.3 Balanced Growth

The balanced-growth path for a deterministic version of the above model will now be characterized. In particular, z and q grow at the (gross) rates γ_z and γ_q, respectively. Clearly, along a balanced-growth path, output, consumption, investment and the capital stocks will all grow, and the amount of labor employed will remain constant. It is convenient to transform the problem into one that renders all variables constant in the steady state.

To find the appropriate transformation, observe that the resource constraint (4) implies that output, consumption, investment, and adjustment costs all have to grow at the same rate, say g, along a balanced-growth path. Then, from the accumulation equation (5) for structures it follows that the stock of structures also have to grow at rate g. Equipment, however, grows faster. From (6) its growth rate, g_e, equals $g\gamma_q$. Finally, the form of the production function (3) implies that $g = \gamma_z g_e^{\alpha_e} g^{\alpha_s}$. Thus, the following restrictions are imposed on balanced growth:

$$g = \gamma_z^{\frac{1}{1-\alpha_e-\alpha_s}} \gamma_q^{\frac{\alpha_e}{1-\alpha_e-\alpha_s}}, \tag{8}$$

and

$$g_e = \gamma_z^{\frac{1}{1-\alpha_e-\alpha_s}} \gamma_q^{\frac{1-\alpha_s}{1-\alpha_e-\alpha_s}}. \tag{9}$$

Given a conjectured growth rate for all variables, one can impose a transformation that will render them stationary. Specifically, define first $\hat{x}_t = x_t/g^t$ for $x_t = y_t$, c_t, i_{et}, i_{st}, and k_{st}, second set $\hat{k}_{et} = k_{et}/g_e^t$, $\hat{q}_t = q_t/\gamma_q^t$, and finally let $\hat{z}_t = z_t/\gamma_z^t$. The household's and firm's choice problems (P1) and (P2), along with the resource constraint (4), can be rewritten in terms of these transformed variables. A globally stable steady state exists for the transformed model which corresponds to an unbounded growth path for the original model.[5]

It follows from the analysis above that the stock of equipment grows over time at a higher rate than output, if the relative price of new equipment in terms of output, or $1/q$, is declining secularly. Thus, the model conforms qualitatively with the long-run observations presented in the introduction. It is also straightforward to check that the properties of the standard neoclassical growth model such as a constant steady-state real interest rate, constant capital and labor share of income, and constant consumption- and investment-to-output ratios are preserved here.

It is interesting to observe that the rental price of a unit of equipment, $zF_1(k_e,k_s,l)$ $= \alpha_e(k_s/k_e)^{\alpha_s}(z^{1/(1-\alpha_e-\alpha_s)}l/k_e)^{1-\alpha_e-\alpha_s}$, must be continually falling along a balanced-growth path since both k_s/k_e and $z^{1/(1-\alpha_e-\alpha_s)}l/k_e$ are declining. It is straightforward to calculate that the rental price of equipment falls along a balanced-growth path at the rate $1/\gamma_q$— assuming that z is constant. How, then, can the real interest rate remain constant? The answer is that the cost of a unit of equipment in terms of consumption goods, or $1/q$, is also declining over time at rate $1/\gamma_q$. Thus, the return from investing a unit of consumption goods in equipment, or $zF_1(k_e, k_s, l)q$, remains constant over time.

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In the class of CES production functions, the Cobb-Douglas case is the only one permitting a balanced-growth path of this sort.

3 The Role of Investment-Specific Technological Change in Economic Growth

How important quantitatively is investment-specific change for U.S. economic growth? What is the impact of other sources of technological progress? By interpreting U.S. postwar data through the above framework, the contribution of these different sources of technological change can be quantitatively assessed.

3.1 Matching the Model with the Data

Care must be taken when matching up the theoretical constructs of the model with their counterparts in the U.S. data. To avoid the problems associated with accounting for quality improvement in new equipment the following general procedure for data construction is adopted. First, the variables in the model's resource constraint, namely y, c, i_e and i_s, are matched up in that data with the corresponding nominal variables from the NIPA divided through by a *common* price deflator. A natural such price in this context is the consumption deflator of nondurable goods and non-housing services, so as to avoid the issue of the accounting of quality improvement in consumer durables. Hence, y, c, i_e and i_s are measured in consumption units *exactly* as they are in the resource constraint (4). The variable q is matched up with Gordon's (1990) equipment price index divided through by the same consumption deflator. Also, since only capital in the business sector is used to produce output in the model, gross housing product is netted out of GNP. Finally, total annual man hours are used for l.

Observe that the variables in the model's resource constraint could be expressed in units of equipment. To do this multiply both sides of the resource constraint through by q to get

$$qc + qi_e + qi_s = qy.$$

The data analogs to qc, qi_e, qi_s, and qy would be now be obtained by deflating the nominal NIPA variables through by Gordon's equipment price deflator. Along a balanced growth path, output measured in equipment units grows at the rate

$$g_{qy} = \gamma_z^{1/(1-\alpha_e-\alpha_s)}\gamma_q^{1+\alpha_e/(1-\alpha_e-\alpha_s)}, \tag{10}$$

which is higher than that given in (8) by a factor of γ_q. The contribution of q to this measure of output growth is now higher, while that of z remains the same. Therefore, a conservative estimate of the contribution of investment-specific technological change to economic growth is obtained when nondurable consumption units are used as a numéraire.

Last, suppose real output is measured in line with standard NIPA definitions. Here real income would defined by $c + i_s + \overline{p}qi_e$, where $\overline{p}$ is some base year price for equipment. The model predicts that in a world with specific-investment change the equipment-investment/GDP ratio, or $\overline{p}qi_e/(c+i_s+\overline{p}qi_e)$, should approach one as time progresses. This is because equipment-investment measured in efficiency units, or qi_e, grows at a faster rate than consumption plus structures measured in consumption units, or $c+i_s$. For the postwar period this prediction is borne out, as Figure 1 illustrates.[6]

3.2 Calibration

To proceed, values must be assigned to the following parameters:

Preferences: β and θ

Technology: α_e, α_s, δ_e, δ_s, and γ_q

Tax rates: τ_k, and τ_l

So as to impose a discipline on the quantitative analysis, the calibration procedure advanced by Kydland and Prescott (1982) is adopted. In line with this approach, as many parameters as possible are set in advance based upon either *a priori* information, or so that along the model's balanced-growth path values for various economic variables assume their average values for the U.S. data over the 1954-1990 period.

The parameters whose values can be fixed upon *a priori* information are:

[6] Some implications for growth accounting that arise from using the NIPA measure of output are discussed in Section 4.3.

(i) $\gamma_q = 1.029$. This number corresponds to the average annual rate of decline in the relative price of equipment prices as measured by Gordon's equipment price series and the deflator for consumer nondurables and nonhousing services. The period used for this calculation is 1954-1983, the period covered by Gordon's study.

(ii) $\delta_s = 0.056$ and $\delta_e = 0.124$. The depreciation rate for structures is obtained using Bureau of Economic Analysis (BEA) capital stock data as follows: Using the accumulation equation for structures from the model and data on real investment and stocks of capital it is possible to back out a series on the implied depreciation rate by setting $1 - \delta_s = \frac{k_{s,t+1} - i_{st}}{k_{st}}$. The value reported above is an average over the sample. Note that the measures here differ from the BEA ones in that the latter use a straight-line depreciation method—where capital is being "written off" in equal installments over the given life of the asset—while in the present model it is assumed that capital depreciates at a constant *rate*. The depreciation rate on equipment is calculated in a similar way.

(iii) $\tau_l = 0.40$. In line with Lucas (1990) the marginal tax rate on labor is set at 40%. Picking the effective marginal tax rate on capital income is more difficult. This is a controversial subject with estimates in the literature varying wildly. For instance for the period 1953-1979, Feldstein, Dicks-Mireaux and Poterba (1983, Table 4, Column 1) present annual estimates of the average effective tax rate on capital income that vary from 55% to 85%. Marginal tax rates would presumably be higher still. Also, for purposes of the current analysis the tax rate chosen should also capture the effects of regulation or other hidden taxes that affect investment. This contentious issue is resolved here by backing out an effective marginal tax rate on capital income which results in the model conforming with certain features of the U.S. data.[7]

[7] Additionally, since 1962 there may have been somewhat of a drift in effective tax rates on capital income favoring the accumulation of equipment vis-a-vis structures. (This drift started with the investment credit for equipment that was introduced in this year.) This issue is abstracted from here. Could such a shift in effective tax rates on capital income be responsible for the observed rise in equipment-to-GNP ratio? Probably not, and this for two reasons. First, the increase in the equipment-to-GNP ratio can be traced back using BEA and NIPA data to at least 1925. (The ratio was 0.33 in 1925 and 0.87 in 1992.) The drift between the effective tax rates on equipment and structures only begins in 1962. Second, a fall in the effective tax rate on equipment should lead to a rise in the relative price of equipment, not the observed

Values remain to be chosen for the parameters β, θ, α_e, α_s, g and τ_k. These values are set so that the model's balanced-growth path displays six features that are observed in the long-run U.S. data. These features are: (i) an average annual growth rate in GNP per hour-worked of 1.24%, (ii) an average ratio of total hours worked to nonsleeping hours of the working-age population of 24%, (iii) a capital's share of income of 30%, (iv) a ratio of investment in equipment to GNP of 7.3%, (v) a ratio of investment in structures to GNP of 4.1%, and (vi) an average after-tax return on capital of 7%.

The equations characterizing balanced growth for the model are:

$$\gamma_q = (\beta/g)[(1-\tau_k)\alpha_e\hat{y}/\hat{k}_e + (1-\delta_e)], \tag{11}$$

$$1 = (\beta/g)[(1-\tau_k)\alpha_s\hat{y}/\hat{k}_s + (1-\delta_s)], \tag{12}$$

$$\hat{\imath}_e/\hat{y} = (\hat{k}_e/\hat{y})[g\gamma_q - (1-\delta_e)], \tag{13}$$

$$\hat{\imath}_s/\hat{y} = (\hat{k}_s/\hat{y})[g - (1-\delta_s)], \tag{14}$$

$$(1-\tau_\ell)(1-\alpha_e-\alpha_s)\frac{\theta(1-l)}{(1-\theta)(\hat{c}/\hat{y})} = l, \tag{15}$$

and

$$\hat{c}/\hat{y} + \hat{\imath}_e/\hat{y} + \hat{\imath}_s/\hat{y} = 1. \tag{16}$$

Equations (11) and (12) are the Euler equations for equipment and structures. The next two equations, (13) and (14), define the corresponding investment to capital stock ratios. The efficiency condition for labor is given by (15). Finally (16) is the resource constraint. The long-run restrictions from the data described above imply the following additional six equations:

decline, since it should stimulate equipment demand.

$$g = 1.0124, \tag{17}$$

$$l = 0.24, \tag{18}$$

$$\alpha_e + \alpha_s = 0.30, \tag{19}$$

$$\hat{\imath}_e/\hat{y} = 0.073, \tag{20}$$

$$\hat{\imath}_s/\hat{y} = 0.041, \tag{21}$$

and

$$(\beta/g) = 1/1.07. \tag{22}$$

Note that (11) to (22) represent a system of twelve equations in twelve unknowns, viz. $\hat{k}_e/\hat{y}$, $\hat{k}_s/\hat{y}$, $\hat{\imath}_e/\hat{y}$, $\hat{\imath}_s/\hat{y}$, l, $\hat{c}/\hat{y}$, g, θ, α_e, α_s, τ_k and β. The parameter values obtained are $\theta = 0.40$, $\alpha_e = 0.17$, $\alpha_s = 0.13$, $\tau_k = 0.42$, and $\beta = 0.95$.[8] The 42% effective tax rate on gross capital income implies a rate on net capital income lying within the range reported by the Feldstein, Dicks-Mireaux and Poterba (1983) study.

3.3 Procedure

A key objective of the analysis in this section is to quantify the contribution to economic growth from investment-specific technological progress. The general strategy is to use data on equipment prices as measure of investment-specific technological change. Hence, a direct

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The values for α_e and α_s are close to those found by Duménil and Lévy (1990) who estimated aggregate functions incorporating equipment, structures, and labor over a 100 year period. They found that a Cobb-Douglas production function with time-varying coefficients fits the data best. For the sub-period under study here the estimated coefficients did not vary much and consequently the Cobb-Douglas production with constant coefficients is an accurate approximation.

observation on q is available. This series, and other data, are then used to impute a series on neutral, or residual, productivity progress by interpreting the postwar experience through the model outlined above.

More precisely, given time series data on y, k_s, k_e, and l, a time series on neutral technological change z can be constructed using the aggregate production function (3). The key step in this calculation is to obtain a series for the equipment stock using the law of motion for equipment (6):

$$k_e' = (1 - \delta_e)k_e + i_e q.$$

Starting from an initial value the series for k_e is constructed by iterating on this equation using the data on i_e and q described above in Section 3.1. The starting k_e was set at its balanced-growth level, given the values of y and q at the beginning of the sample.[9] Finally, given estimates for γ_z and γ_e, the balanced-growth formula for the growth rate of output, equation (8), is used to calculate the long-run implications of each of the two forms of technological change.

3.4 The Results

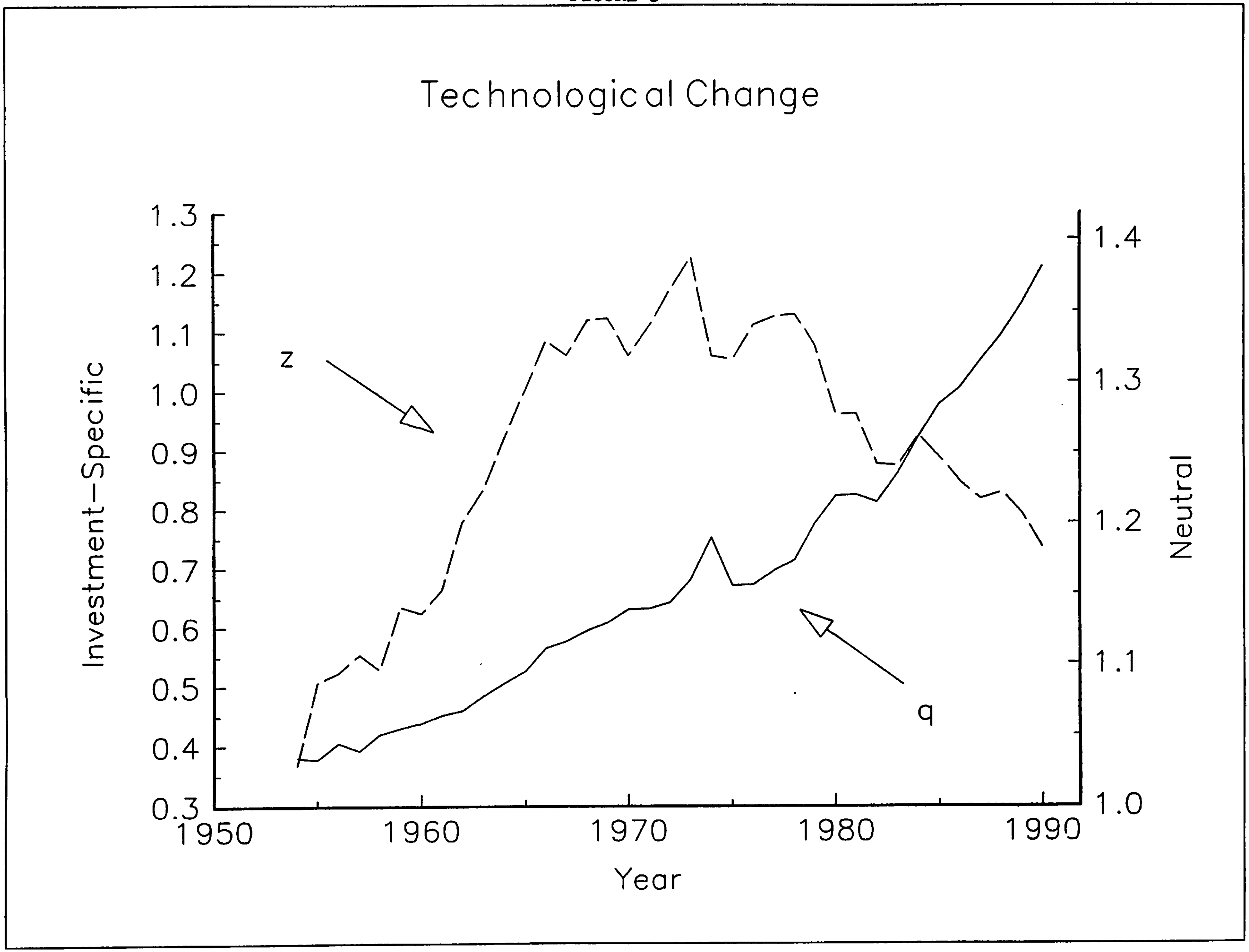
The data analysis focuses on two related questions. First, does the postwar picture of total factor productivity growth change when an explicit treatment of investment-specific technological progress is incorporated into the analysis? Second, how much of long-run growth is accounted for by investment-specific technological change?

Figure 3 plots the q and the computed z series. Two observations are immediate. First, z does not display a strong long-run trend. The average annual growth in neutral productivity change is 0.39%. By comparison, the growth rate in investment-specific productivity is 3.21%.

The second, and most noticeable, feature of Figure 3 is the dramatic downturn in total

9 An alternative is to use the standard measure for the equipment stock in that year, which yields very similar results for the measurement of z.

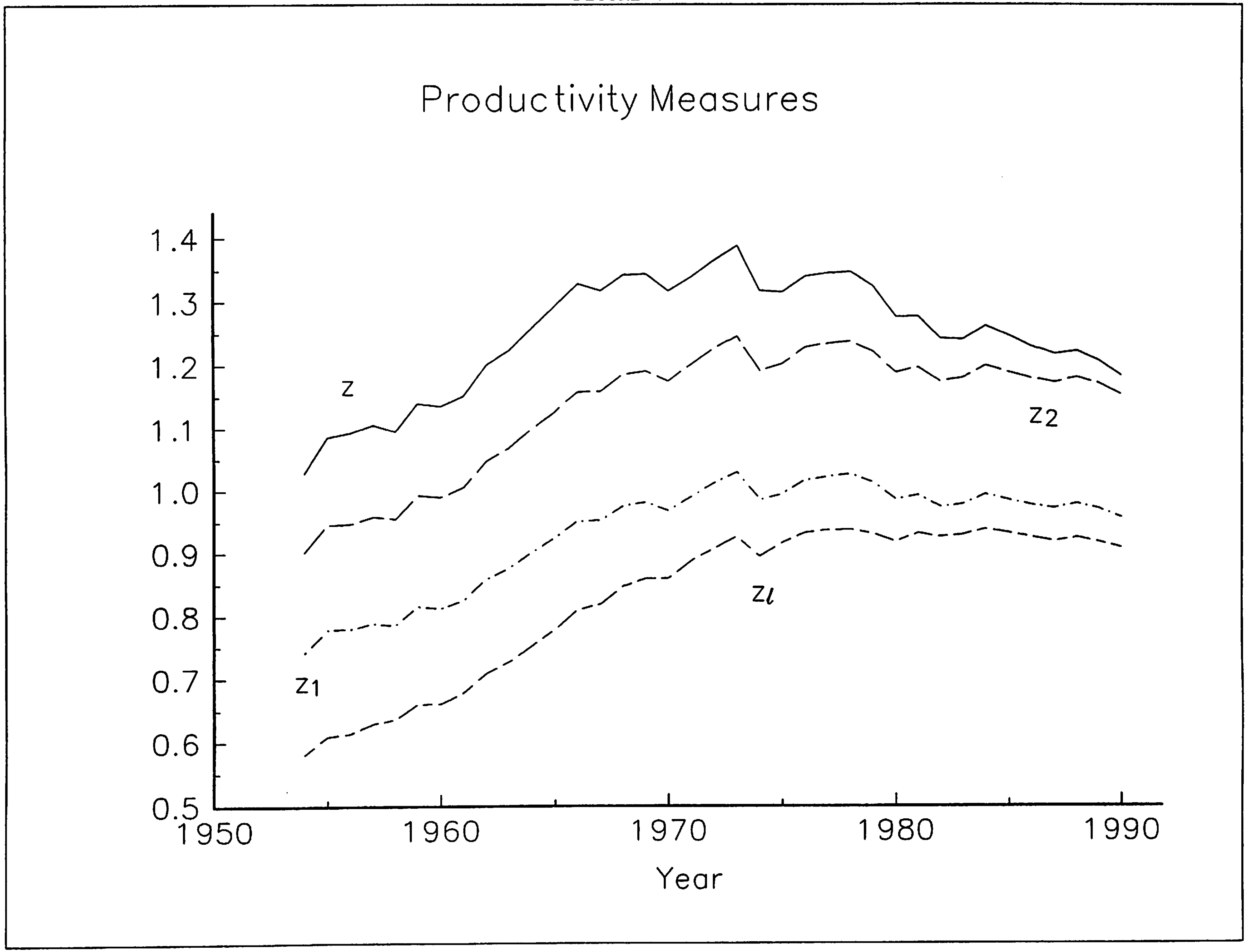
FIGURE 3


Technological Change
z
q
Investment-Specific
Neutral
Year
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1.4
1.3
1.2
1.1
1.0
1950
1960
1970
1980
1990

factor productivity which began in the seventies and continued without interruption until the end of the sample. Two factors in the current analysis contribute to this phenomenon. First, note that investment-specific technological change was high when total net productivity growth was low; i.e., growth in the q series accelerated at the same time as there was a productivity slowdown in the z series. Thus, when changes in q are explicitly accounted for, the slowdown in z tends to be more pronounced. Second, equipment plays an important role, quantitatively, in the analysis. Specifically, had the current analysis treated equipment and structures equally in production, as is implicitly done in conventional analyses where these two capital stock are simply aggregated together, the magnitude of the downturn would not be as large.

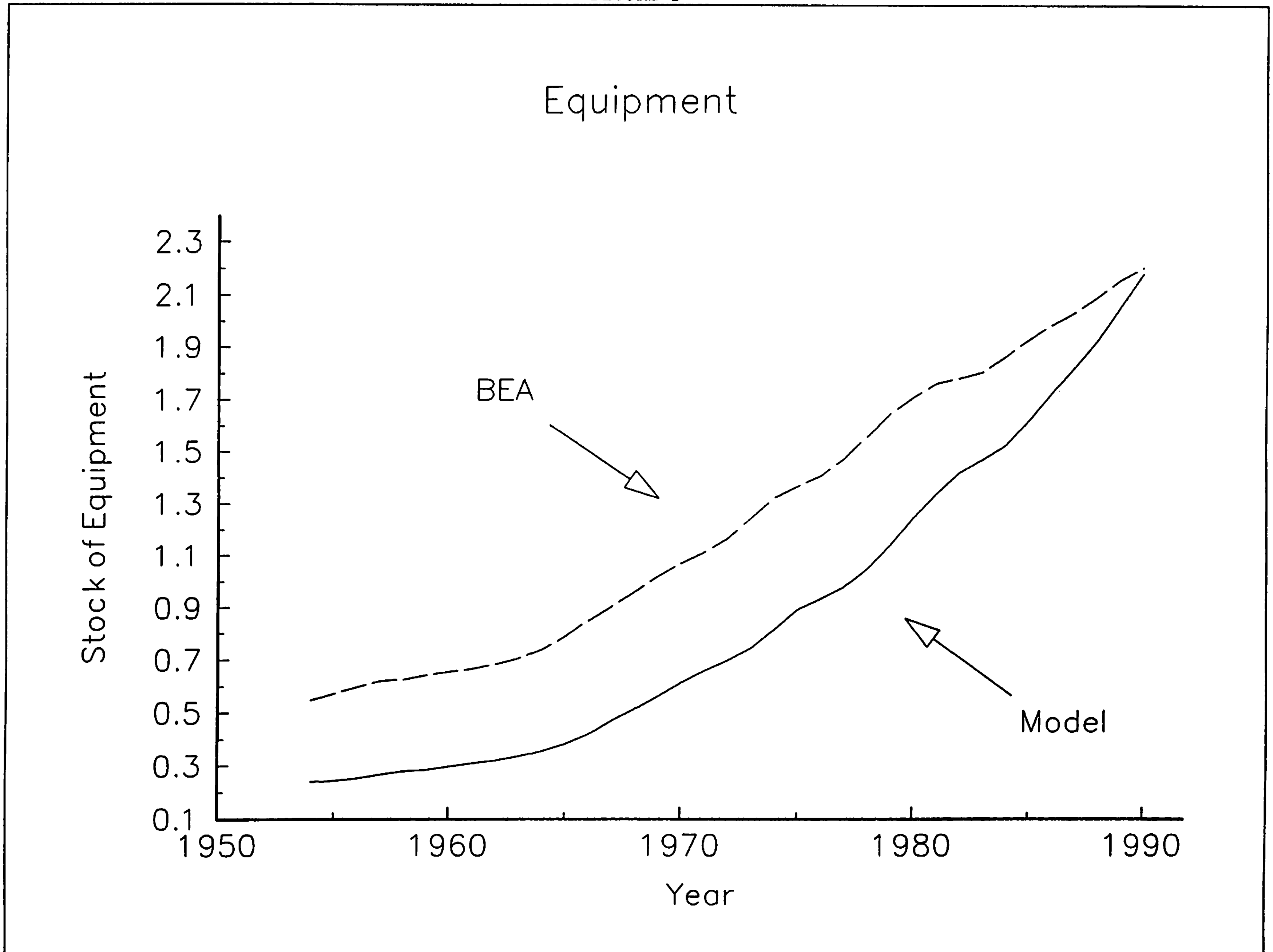
The importance of properly incorporating capital into growth accounting can be illustrated as follows. Suppose that output is produced using only labor according to the constant returns-to-scale production function $y = z_l l$. Here the Solow residual z_l corresponds to average labor productivity, y/l, as conventionally measured, which grew at 1.24% per year over the postwar period. Figure 4 plots z_l. Observe that productivity growth slows down in the 70's, but remains positive. Next, consider the standard one sector growth model. Here output is produced according to $y = z_1 k^{\alpha} l^{1-\alpha}$, where k represents standard measure of the *combined* stocks of equipment and structures. Now, the rate of disembodied technological change is 0.71% per year on average. Figure 4 also plots this standard measure of the Solow residual or $z_1 = y/(k^{\alpha} l^{1-\alpha})$. The productivity slowdown is now more apparent. Now, disaggregate the capital stock into equipment and structures and assume the aggregate production function is given by $y = z_2 k_e^{\alpha_e} k_s^{\alpha_s} l^{1-\alpha_e-\alpha_s}$. If one assumes that the BEA measures of equipment and structures are correct, then the Solow residual grew at 0.68% annually—see Figure 4. Finally, if the stock of equipment is adjusted in line with Gordon's data for investment-specific technological change the growth rate in $z = y/\left[k_e{}^{\alpha_e} k_s^{\alpha_s} l^{1-\alpha_e-\alpha_s}\right]$ drops to 0.33%. The difference between the BEA measure for the stock of equipment and the measure constructed here, which reflects better the improvement in quality of equipment, is shown in Figure 5. The productivity slowdown, as captured by Figure 4, becomes dramatic.

FIGURE 4



Productivity Measures
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
1950
1960
1970
1980
1990
Year
z
z2
z1
zl

FIGURE 5


Equipment
Stock of Equipment
2.3
2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1
1950
1960
1970
1980
1990
Year
BEA
Model

However dramatic the behavior of neutral, or residual, productivity change, the main goal here is not to decompose this variable. The effects of accounting for changes in labor quality, though, as captured by Jorgenson, Gollop and Fraumeni (1987) index will be reported. This index in labor quality shows a slowdown starting in the late sixties: From an average yearly growth of 0.7% during the 1954-1968 period, the series's growth rate drops to 0.25% between 1968-1989. When the labor input measure is adjusted to incorporate the Jorgenson-Gollop-Fraumeni (1987) labor quality index the pattern of z remains the same. Although the average growth of the residual is now close to zero, there is still a sharp rise prior to the earlier seventies followed by unabated productivity regress.

Using formula (8) and the average growth rates for q and z, 3.21 and 0.39, respectively, one can obtain estimates of the contributions that the two sources of productivity change made to growth in output per hour worked. These estimates are approximations, given that (8) refers to balanced growth while the technology growth rates are sample averages. The actual average growth rate of output per hour over the 1954-90 sample period is 1.24% per year. With only investment-specific technological change at work [i.e., assume $\gamma_z = 1$ in (8)] output per hour would have grown at 0.77% per year. The corresponding figure for neutral technological change is 0.56%. Hence, investment-specific change technological change contributes about 58% of all output growth with neutral change providing the rest.[10]

4 Traditional Growth Accounting

How should investment-specific (or capital-embodied) technological change be modeled? As Hulten (1992) has highlighted, two distinct frameworks have been used to study this form of technological change. The first was developed by Solow (1959), and is similar to the approach taken here. The second approach, which has dominated the practice of growth

10 Note that adding up the contributions of the two shocks yields a growth rate in output per hour of 1.34%. The difference between this number and the actual observed figure of 1.24% is due to the balanced-growth approximation.

accounting [e.g. see Gordon (1990)], is due to Domar (1964) and Jorgenson (1966). Using the notation developed above, both frameworks express the law of motion for equipment as

$$k_e' = (1 - \delta_e)k_e + i_e q. \tag{23}$$

The models differ in the way they express the resource constraint. In line with the current analysis, the resource constraint for the Solow model reads

$$c + i_e = zF(k_e, l), \tag{24}$$

where for simplicity structures have been dropped from the analysis. The resource constraint for the Domar-Jorgenson model appears as

$$c + i_e q = zF(k_e, l). \tag{25}$$

Thus, the sole difference between the two models is the inclusion of q in the resource constraint.

Which model, then, is better suited to analyze the macroeconomic effects of investment-specific technological change? The analysis conducted below suggests that both theory and data speak clearly in favor of the Solow model.

4.1 Theory

When embedded into a fully specified general equilibrium setting, the Domar-Jorgenson specification does not allow for investment-specific technological change to operate as an engine of growth. This can be seen by substituting (23) into (25) to obtain

$$c + k_e' - (1 - \delta)k_e = zF(k_e, l). \tag{26}$$

Equation (26) is the economy's intertemporal production possibility set. Given an initial value for the equipment stock, it completely describes all feasible paths for consumption and capital. Note that q is absent in (26)! Thus, the economy's ability to produce consumption goods is unaffected by shifts in q: any movement in q will be fully offset by an opposite movement in i_e, a point that will be returned to in Section 4.2. Thus, the general equilibrium view adopted here leads to the conclusion that movements in q cannot in any way affect consumption or capital accumulation in the Domar-Jorgenson model. In particular, (26) shows that the production possibility set is identical to that of the standard one-sector growth model. This result follows from the specification that i_e and q enter *everywhere* in the multiplicative form $i_e q$, and thus the model's equilibrium dictates a value for the product.

Note that entering q into the resource constraint (25) amounts to assuming that resources need to be expended in order to develop the new technologies, a point made by Hulten (1992). Is this assumption reasonable? To answer this question, first join the resource constraint and the capital accumulation equation into the more general form

$$G(c, k_e, k_e', l, z, q, R(q, z)) = 0, \tag{27}$$

Here $R(q, z)$ is the amount of resources that are needed to attain the level of technology level indexed by (q, z). The Domar-Jorgenson framework makes two assumptions on the resource cost of technological change. The first is to drop z as an argument in R. The second is to assume that i_e and R enter the function G in the multiplicative form qi_e. The first assumption treats embodied and disembodied technological change in an asymmetric fashion; viz., the former requires resources while the latter does not. The second assumption implies that the resource cost of increasing q by x percent is xi_e, which exactly equals the gain (measured in consumption units) that the increase in q gives by adding xi_e to the stock of new equipment. The second assumption, therefore, implies that changes in q yield no net gain to consumers. Note also that the Domar-Jorgenson model differs from conventional models of costly technological change in an important respect: resources must be expended to maintain a certain *level* rather than *rate of change* (or innovation) in technology.

A goal of the current paper is to estimate how much of growth was due to q and how much was due to z. Given this, q and z are treated in a symmetric fashion. For simplicity, rather than model R&D explicitly, it is assumed here that technological change of both kinds is both exogenous and costless. With this formulation, equation (27) reads

$$G(c, k_e, k_e', l, z, q) = 0.$$

To conclude, the Domar-Jorgenson framework does not admit the possibility of investment-specific technological change. In particular, the relative price of an efficiency unit of investment goods in terms of consumption does not decline—it always equals one. An added consequence for the balanced-growth path of this model is that the investment-to-GDP ratio does not increase as in the data, but it remains constant.

4.2 Practice

The current study finds that approximately 60% of growth in aggregate output can be accounted for by investment-specific technological change. In contrast, Hulten (1992) finds that about 20% of residual manufacturing growth is due equipment quality improvement. How can these results be reconciled?

Traditional growth accounting uses an aggregate production function of the form

$$y = zF(\psi k_u, l) \tag{28}$$

to decompose shifts in y into underlying changes in k_u, l, ψ and z, where ψ an index of capital-embodied technological change and k_u is a measure of the capital stock *un*adjusted for quality. The quality-unadjusted capital stock is the "historical cost" of capital, implying $k_{ut} = \sum_{s=1}^{t} i_{t-s}(1-\delta)^{s-1} + k_0$. Due to the presence of investment-specific technological change the capital stock in efficiency units is larger than this. In particular, iterating on (23) yields $k_{et} = \sum_{s=1}^{t} q_{t-s} i_{t-s}(1-\delta)^{s-1} + k_0$. The ratio of these two measures is taken as an index of capital-embodied technological change so that $\psi = k_e/k_u$. Note that along a balanced growth path ψ will grow at the same rate as q. Expressing (28) in log-difference form gives

$$\widehat{y} = \alpha\widehat{\psi} + \alpha\widehat{k}_u + (1-\alpha)\widehat{l} + \widehat{z}, \tag{29}$$

where α is capital share's of income and $\widehat{x}$ represents the log difference of x. Traditional growth accounting takes the term $\alpha\widehat{\psi} + \widehat{z}$ as representing growth due to productivity change.

Of this the fractions $\alpha\widehat{\psi}/(\alpha\widehat{\psi}+\widehat{z})$ and $\widehat{z}/(\alpha\widehat{\psi}+\widehat{z})$ are attributed to investment-specific and neutral technological change, respectively. This calculation controls, so to speak, for growth in inputs. It amounts to assuming that input growth is exogenous.

Controlling for the growth in inputs has important consequences for growth accounting. When this is done, equation (29) cannot distinguish between the Domar-Jorgenson and Solow models. To see this, consider equation (29) in the context of the Domar-Jorgenson model. Here the contribution of investment-specific technological to economic growth should be identically zero, as established Section 4.1. Traditional growth accounting, however, will estimate the contribution to be $\alpha\widehat{\psi}/(\alpha\widehat{\psi}+\widehat{z})$. The mistake is that in the Domar-Jorgenson model changes in q should be exactly offset in general equilibrium by changes in i_e, and hence implied changes in $\widehat{\psi}$ are offset one to one by changes in $\widehat{k}_u$.

Will traditional growth accounting give the correct answer for the Solow model? Using the results in Section 2.3 it transpires that along a balanced growth path $\widehat{y}=\ln g$, $\widehat{k}_u=\ln g$, $\widehat{\psi}=\ln\gamma_q$, $\widehat{z}=\ln\gamma_z$, and $\ln\widehat{l}=0$.[11] Next, substituting into (29) for $\widehat{y}$, $\widehat{\psi}$, $\widehat{k}_u$,$\widehat{l}$, and $\widehat{z}$ and solving yields $\ln g=[1/(1-\alpha)](\alpha\ln\gamma_q+\ln\gamma_z)$, the log of the answer given in (8). The *fractions* of growth due to investment-specific and neutral technological change are therefore given by $\alpha\ln\gamma_q/(\alpha\ln\gamma_q+\ln\gamma_z)$ and $\ln\gamma_z/(\alpha\ln\gamma_q+\ln\gamma_z)$. Thus, if the data generating mechanism is described by the Solow model, traditional growth accounting gives the correct answer. In general, however, this need not be the case.

Now, suppose that the world is described by the Solow model. Why does Hulten (1992), who uses traditional growth accounting methodology, then find that only 20% of output growth was due to investment-specific technological change as opposed to the 60% found here? First, the Domar-Jorgenson and Solow models call for output to be measured in different ways. The key issue is whether or not to adjust output for quality change. The Domar-Jorgenson model demands that you do, and the Solow model dictates that you do not.[12]

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11 The analysis assumes no population growth. This amounts to measuring output and capital in per-capita terms.

12

Second, Hulten (1992) studies the manufacturing sector whereas the current work focuses on the aggregate economy. His data is on gross output, whereas value-added data is used here. These differences are important since they have implications for the measurement of equipment's share of income. In particular, equipment's share from gross output, which includes intermediate goods, will be smaller than its share from value-added. As has been noted by Hulten (1979), when doing growth accounting with intermediate goods any "post-mortem assessment of the sources of growth" should recognize that part of the expansion in intermediate goods is due to technological change. Thus, whether one approach is better than the other will depend upon how much of the increase in the quantity of intermediate goods derives from the improvement in quality of equipment.[13]

Finally, how much of the difference in the results can be attributed to each of these factors? Changing the weight on equipment in Hulten's analysis from 0.11 to 0.17 increases his number from 20% to 43%.[14] Additionally, if the quality adjustment is dropped from his computations the figure rises from 43% to 66%. This is close to the current finding.

4.3 On the Use of NIPA Data

The Domar-Jorgenson framework suggests that output should be adjusted for equipment quality. In principle this adjustment is done in NIPA data too. Suppose that the world is characterized by the Solow model described above. The NIPA definition for income in this world would appear as $c+\overline{p}qi_e$, where $\overline{p}$ is some base year price for equipment. Now, let this concept of income be identified with an aggregate production function, as is conventionally

In line with (25), Hulten (1992) uses as a measure of output the sum of consumption and investment in *efficiency* units.

13

In principle, a multisector general equilibrium model could have been developed, where a portion of each sector's output is used as intermediate inputs in other sectors. Part of the growth in these inputs would result from investment-specific technological change. When assessing the role of investment-specific technological change for the aggregate economy, the accounting procedure adopted here would attribute growth from these sources to the underlying forms of technological change. Provided the role of intermediate inputs is similar in all sectors, the use of a one-sector model and value-added data should provide roughly the same answer as the more elaborate multisector framework.

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These calculations are based on the material presented in Hulten (1992), Tables 2, 3, 4 and 5.

done in the growth accounting literature. Specifically, set $y_{NIPA} \equiv c + \overline{p}qi_e = zF(k_e, l)$. Observe that if $\overline{p} = 1$ (an innocuous normalization) this equation is identical to the resource constraint used in the Domar-Jorgenson model. When using this procedure to account for the observed growth in y_{NIPA}, some of the growth in q will be identified as growth in z. This occurs because the growth of the investment component of output is inflated by the growth in q when the accompanying fall in p is not taken into account. Therefore, the use of NIPA data in conventional growth accounting will cause investment-specific technological change to appear as neutral. [This effect is stronger in Hulten's (1992) analysis, where the quality adjustment is larger than in the NIPA.] Note that this problem does not arise when output is measured in consumption units

5 Future Directions

A simple one-sector model with both neutral and investment-specific technological change was shown to be capable of explaining the simultaneous decline in the fall of equipment prices and the rise in the equipment-to-GNP ratio along a balanced-growth path. What avenues do these results suggest for future analysis of the origins and aggregate importance of investment-specific productivity improvements? In this section, some interesting possibilities are briefly discussed.

The starting point for the subsequent analysis is a two-sector model where one sector produces consumption goods and structures, and the other manufactures equipment. The one-sector model studied above is a special case of this more general framework. So too are the well-known convex endogenous-growth models studied in Rebelo (1991) and in Jones-Manuelli (1990,1994). Can such a structure help explain the above stylized facts, perhaps even without resorting to investment-specific technological change? It turns out that differences in the share parameters across sectors, alone, can lead to declining relative prices for equipment goods, if, roughly speaking, the equipment-producing sector uses equipment more intensively than the other sector. The balanced growth rates of output and the relative price of equipment can be characterized in terms of the underlying share parameters for the model. The differences in share parameters needed to rationalize the observed relative price decline and output growth rate are found to be empirically implausible.

Next, some modifications to the basic two-sector framework that can potentially explain the stylized facts in question are suggested. First, a model where growth is driven explicitly by the accumulation of human capital is outlined. In order for such a model to fit the facts, there has to be a connection between human capital and equipment investment; e.g., the equipment producing sector needs to be much more intensive in its use of human capital than the consumption goods sector. Second, a framework where growth is driven by externalities in the investment goods sector is spelled out. Last, a paradigm that is oriented toward explaining investment-specific technological change directly as a consequence of underlying profit-maximizing R&D decisions undertaken by firms is presented.

5.1 Two-Sector Models

Consider the following two-sector model. The first sector produces consumption goods and structures. Sector One's resource constraint appears as

$$c + i_s = zA_1 k_{1e}^{\alpha_e} k_{1s}^{\alpha_s} l_1^{1-\alpha_e-\alpha_s},$$

where k_{1e}, k_{1s}, and l_1 represent the inputs of equipment, structures and labor used in this sector. Sector Two produces equipment. The resource constraint for the equipment-producing sector reads

$$i_e = zqA_2 k_{2e}^{\beta_e} k_{2s}^{\beta_s} l_2^{1-\beta_e-\beta_s}, \tag{30}$$

where k_{2e}, k_{2s}, and l_2 represent factor the inputs of equipment, structures and labor. Next, aggregate investment in equipment and structures is defined by $k'_{1e} + k'_{2e} = (1-\delta_e)(k_{1e} + k_{2e}) + i_e$, and $k'_{1e} + k'_{2s} = (1-\delta_s)(k_{1s} + k_{2s}) + i_s$. Finally, labor market clearing requires that $l_1 + l_2 = l$. The rest of the model remains the same as before, with due alteration.

It is easy to show that when $\alpha_e = \beta_e$ and $\alpha_s = \beta_s$ the model is isomorphic to the one-sector model used above. This follows from the fact that the capital-labor ratios will be equal in the two sectors in equilibrium. Furthermore, this structure allows long-run growth even when $\gamma_z = \gamma_q = 1$; i.e., there can be endogenous growth. A necessary condition for this is that either: (i) $\alpha_s = 1$, (ii) $\beta_e = 1$, or (iii) $\alpha_e + \alpha_s = \beta_e + \beta_s = 1$. Condition (i) amounts to the "Ak" model studied in Rebelo (1991) and in Jones-Manuelli (1990). This model does not have a declining relative price of capital. Condition (ii) implies another of the models in Rebelo (1991) and Jones-Manuelli (1994), which does allow for a declining relative price of equipment capital together with an increasing equipment-to-GNP ratio, provided that $\alpha_e < 1$. Finally, condition (iii) implies that the relative price of capital and the equipment-to-GNP ratio are stationary along a balanced growth path.

Following the procedure outlined in Section 2.3, the balanced growth rates of output and equipment are uniquely determined by

$$g_y = \gamma_z^{(1+\alpha_e-\beta_e)/(1-\alpha_s-\beta_e+\beta_e\alpha_s-\alpha_e\beta_s)}\gamma_q^{\alpha_e/(1-\alpha_s-\beta_e+\beta_e\alpha_s-\alpha_e\beta_s)}, \tag{31}$$

and

$$g_e = \gamma_z^{(1-\alpha_s+\beta_s)/(1-\alpha_s-\beta_e+\beta_e\alpha_s-\alpha_e\beta_s)}\gamma_q^{(1-\alpha_s)/(1-\alpha_s-\beta_e+\beta_e\alpha_s-\alpha_e\beta_s)}, \tag{32}$$

provided that $(1 - \alpha_s - \beta_e + \beta_e\alpha_s - \alpha_e\beta_s) = (1 - \beta_e)(1 - \alpha_e - \alpha_s) + \alpha_e(1 - \beta_e - \beta_s) > 0$. It is straightforward to verify that this condition is equivalent to requiring that the above necessary condition for endogenous growth is *not* satisfied. In other words, endogenous, balanced growth can only occur in this convex growth model if $\gamma_z + \gamma_e = 1$; i.e., if there is no exogenous technological change.

Observe that the equipment-to-GNP ratio will unambiguously rise provided that the equipment-producing sector is more capital intensive than the consumption goods sector, or when $\beta_e + \beta_s > \alpha_e + \alpha_s$. Next, it is easy to calculate that the decline in the relative price of equipment is

$$\gamma_p = \gamma_y^{(\alpha_e+\alpha_s-\beta_e-\beta_s)/(1+\alpha_e-\beta_e)}\gamma_q^{-1/(1+\alpha_e-\beta_e)}. \tag{33}$$

Note that when equipment and structures have the same share of income in both sectors the above two-sector model collapses to the one sector framework used in the quantitative analysis. That is, if $\alpha_e = \beta_e$ and $\alpha_s = \beta_s$ then equations (31), (32) and (33) reduce to (8), (9) and $\gamma_p = 1/\gamma_q$.

The question now is whether a model without investment-specific technological change can *realistically* account for the observed decline in the relative price of capital in the absence of investment-specific technological change. Rewriting (33) yields the condition

$$\frac{(\alpha_e + \alpha_s) - (\beta_e + \beta_s)}{1 + \alpha_e - \beta_e} = \frac{\ln \gamma_p}{\ln \gamma_y}, \tag{34}$$

which holds for both the exogenous- and the endogenous-growth versions of the model. Recall that for the postwar period, $\gamma_p = 1/1.029$ and $\gamma_y = 1.0164$, which implies $\ln \gamma_p / \ln \gamma_y \simeq -1.76$. Hence, in order to generate the observed decline in the price of equipment relative to the increase in income, the shares of equipment and structures must be very different across the two sectors. This is shown in Table 1, which illustrates various combinations of $(\beta_e + \beta_s) - (\alpha_e + \alpha_s)$, $(\beta_e - \alpha_e)$, and $(\beta_s - \alpha_s)$ that are consistent with equation (34). This table also shows the upper bound on labor share in the equipment sector that is consistent with these combinations—see the column marked $\max(1 - \beta_e - \beta_s)$.

TABLE 1 HERE

The prospect for explaining the relative price decline with a two-sector model based on differences in share parameters looks bleak, given the implausibly large differences required in structure of production across sectors. It requires: (i) that the equipment-producing sector is more capital intensive than the other sector, and (ii) that labor's share of income is very low in the equipment sector. In sharp contrast, Baxter (1992) and Hornstein and Praschnik (1994) report labor shares in capital goods production of about 0.70 and somewhat *lower* capital shares in capital goods production than in production of non-capital goods.

5.2 Human Capital Accumulation

Consider now a version of the above two-sector economy with two types of labor: viz., skilled and unskilled. Let unskilled agents work in Sector One and skilled agents in Sector Two. Skilled agents can upgrade their human capital according to the law of motion

$$h_2' = H(e_2)h_2, \text{ with } H' > 0 \text{ and } H'' \leq 0,$$

Difference in Capital Share Parameters Across Sectors			Maximum Labor Share in Equipment Sector
Total	Equipment	Structures	
$(\beta_e + \beta_s) - (\alpha_e + \alpha_s)$	$\beta_e - \alpha_e$	$\beta_s - \alpha_s$	$\max(1 - \beta_e - \beta_s)$
0.10	0.94	-0.84	0.06
0.35	0.80	-0.45	0.20
0.65	0.63	0.02	0.35
0.90	0.49	0.41	0.10

Table 1: **Structure of Production**

where h_2 represents a skilled agent's stock of human capital in the current period and e_2 denotes the time he devotes to human capital formation. Let the resource constraint for the equipment-producing sector read

$$i_e = zA_2 k_{2e}^{\beta_e} k_{2s}^{\beta_s} (h_2 l_2)^{1-\beta_e-\beta_s}, \tag{35}$$

where l_2 denotes the amount of raw skilled labor used in equipment production. As skilled agents make investments in human capital, the production of equipment will be undertaken ever more efficiently. Observe that (35) can be rendered equivalent to (30) by setting $q = h_2^{1-\beta e-\beta_s}$. It is easy to see that such a framework will be similar in many respects to the one used in the quantitative analysis.

5.3 Investment-Specific Externalities

Another set of endogenous growth models have emphasized productive externalities [see e.g. Romer (1986)]. Again within a two-sector framework, suppose that the consumption sector is the same as the above model but that

$$i_e = EzA_2 k_{2e}^{\beta_e} k_{2s}^{\beta_s} l_2^{1-\beta_e-\beta_s},$$

where E is a variable which is taken as given by the individual profit center but which is determined by aggregate behavior. This externality could take various forms and be given various interpretations. One specific formulation has $E_t \equiv (\sum \mu_{t-s} i_{e,t-s})^\rho$ with $\sum \mu_{t-s} = 1$; i.e., productivity in the investment sector is a weighted average of past production in the sector. This formulation can be motivated by learning-by-doing arguments. It is easy to show that this model formulation does give rise to a declining relative price of equipment along a balanced growth path as long as z grows at a constant rate. If z does not grow, the model is consistent with long-run growth if ρ is large enough, and balanced growth with a declining relative price of equipment if $\rho + \beta_e + \beta_s = 1$.

5.4 Research and Development

A more direct way of modeling growth in investment-specific technology is based on R&D. In such a model, decisions to expend resources in order to develop new types of equipment would be made at the level of private firm. Most of the existing R&D models employ setups with monopolistic competition [that build upon Romer (1987)]. Hence, in this setting there would be a range of different types of equipment, each associated with a producer who makes a product-specific R&D decision. In this setup, new products are not priced at marginal cost, and therefore relative price movements may also capture movements in markups. Therefore, this could make the identification of the rate of relative price decline with the rate of investment-specific technological change more problematic.

More specifically, suppose evermore efficient equipment can be made through time, and that the R&D decisions at each point in time involve deciding how much more efficient to make the next generation of equipment. If equipment of type i is associated with an efficiency level $q(i)$, the latter can be specified to evolve recursively as:

$$q'(i) = H(q(i), \bar{q}, n(i)).$$

Here, $\bar{q}$ is the average technology level across equipment types (this formulation hence allows for externalities in R&D), and $n(i)$ is the amount of labor resources currently used in R&D for type-i equipment good. Under certain assumptions on H, a monopolistic competition version of this framework leads to a balanced-growth path with constant percentage markups [see Krusell (1992)]. A calibrated balanced-growth version of this model would therefore find the same rate of investment-specific technological change as found in this paper.

6 Conclusions

The analysis in this paper was motivated by two key observations. First, over the long run the relative price of equipment has declined remarkably while the equipment-to-GNP ratio has risen. This suggests that investment-specific technological change may be a factor in economic growth. Second, the short-run data display a negative correlation between the price for equipment on the one hand, and equipment investment or GNP on the other. This also hints that investment-specific change may be a source of economic fluctuations.

A simple vintage capital model was constructed here that has the property that the equipment-to-GNP ratio increases over time as the relative price of new capital goods declines. The standard features of the neoclassical growth were otherwise preserved. The balanced-growth path for the framework under study was calibrated to the long-run U.S. data. A growth accounting exercise was then conducted with the model. It was found that approximately 60 percent of postwar productivity growth can be attributed to investment-specific technological change. This result may indicate where the highest return on future theorizing about engines of growth lies. Also, a more striking picture emerges of the much discussed productivity slowdown that started in the 1970's. Once the recent rapid improvement in the quality of capital goods is taken into account, the decline in the productivity of other factors is dramatic. These findings point to a very specific and potentially important source of economic growth. Although the analysis was undertaken within the context of a simple framework where investment-specific technological change arose exogenously some suggestions were made for making this concept endogenous. Taking these more elaborate models, which allow for human capital formation, endogenous R&D, monopolistic competition, etc., to data should constitute an important robustness test on the findings obtained here.

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A DATA

Sample: 1954-1990.

The empirical counterparts of the theoretical variables used in the data calculations are the following:

y : nominal GNP net of gross housing product divided by the implicit price deflator for nondurable consumption goods and nonhousing services—base year 1987.

c : nominal consumption expenditure on nondurables and nonhousing services divided by their implicit price deflator—base year 1987.

i_e : nominal investment in producer durable equipment divided by the implicit price deflator for nondurable consumption goods and nonhousing services—base year 1987.

i_s : nominal investment in producer structures in 1987 dollars.

i : total investment in 1987 dollars. Thus, $i = i_e + i_s$.

k_s : net stock of producer structures in 1987 dollars.

k_e : net stock of equipment in 1987dollars. This series was generated using the procedure outlined in Section 3.

l : total hours employed per week—Household Survey data.

q : implicit price deflator for nondurable consumption goods and nonhousing services divided by Robert J. Gordon's (1990, Ch. 12, Table 12.4) index of nominal prices for producer durable equipment. Since Gordon's index is only computed through 1983, a correction of the NIPA measures for producer durable equipment was used for the remainder of the sample.[15]

[15] The estimates for the parameters were obtained using data for the sample period 1954 to 1990. Gordon's price index was used for the 1954-83 subperiod and a correction of NIPA price measures for the 1984-90 subperiod. The correction to the NIPA measures involved adjusting downwards the growth rates for the indexes in the producer durable equipment (PDE) categories by 1.5 percent. An exception was the computers category, which already incorporates the quality adjustment used in Gordon (1990). This adjustment to the NIPA numbers was suggested by Robert Gordon. Moreover, the new index for 1984-1990 was constructed by taking an average of the implicit PDE price deflator (IPD) and the fixed-weight price index (PPI) for PDE.

Notes to Appendix A:

1. Because of the approach taken here to quality improvement in equipment, standard constant price output and equipment data cannot be used in this framework as the corresponding variables y and i_e. These theoretical constructs should be matched with quantities expressed in terms of their cost in consumption units. Correspondingly, y and i_e were computed by deflating nominal GNP and equipment investment by the consumption deflator. For structures this problem does not exist, but for consistency the same procedure was followed.

2. The depreciation rates δ_e and δ_s were computed using BEA constant price data on both equipment and structures. BEA equipment figures were used to compute the geometric depreciation rates used for the model that correspond to straight-line rates.

This average reflects the desire to replicate the more elaborate Tornquist index used in Gordon (1990).