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The vintage effect in TFP-growth: An analysis of the age structure of capital

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Abstract

The age structure of capital plays an important role in the measurement of productivity. It has been argued that the slowdown in the 1970s can be ascribed to the aging of the stock of capital. In this paper, we incorporate the age structure in productivity measurement. One proposition proves that Nelson's [Nelson, R.R., 1964. Aggregate production functions and medium-range growth projections. American Economic Review 54 (September), 575–605] formula is only an approximation. Our final proposition shows that inclusion of the vintage effect prompts an upward correction of measured productivity growth in times of an aging stock of capital. Here capital ages if the investment/capital ratio falls short of the inverse of the capital age, as a first proposition shows. The analysis rests on a rigorous accounting for vintages. We translate the Bureau of Economic Analysis' age of capital data into a measure of rates of obsolescence. Empirically, the correction of productivity growth for the vintage effect requires an estimate of the obsolescence and depreciation parameters on the basis of age data. The results indicate that the use of capital stock in efficiency units does cause some smoothing of total factor productivity growth over time. In the 1950s, when investment accelerated, the vintage-adjusted capital growth rate well exceeded the BEA growth rate, and vintage-adjusted

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TFP-growth is significantly lower than unadjusted TFP-growth. The measured productivity slowdown of the 1970s is somewhat ameliorated.

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1. Introduction

An important source of technological advance is through new technology embodied in investment goods (see, for example, Solow, 1960; Jorgenson, 1966). It is also consistent with the "vintage effect," which states that new capital is more productive than old capital per (constant) dollar of expenditure.[1] If the capital stock data do not correct for vintage effects, then a negative correlation should be observed between the rate of technological gain and the change in the average age of capital.

Several papers have attempted to measure the contribution of the vintage effect to U.S. productivity growth, particularly as a factor in explaining the productivity slowdown of the 1970s. A number of different approaches have been used over the years. We discuss five of them below. First, Kendrick (1980) relied on a growth accounting approach. Using the average age of capital goods as an indicator of the rate of diffusion of new technology, he found that between 1948 and 1966, the average age declined by 3 years, contributing 0.25 percentage points to the overall productivity growth rate. Between 1966 and 1973 the decline in average age slowed to 1 year and between 1973 and 1978 there was no decline in the average age of capital stock. Clark (1979), also using growth accounting methods and assuming that new capital stock is 1% more productive than last year's capital stock, estimated a somewhat smaller vintage effect than Kendrick did. He estimated that of the 0.66-point decline in the labor productivity growth rate between 1948–1965 and 1965–1973, the vintage effect explained 0.09 points; of the 1.17-point decline between 1965–1973 and 1973–1978, the vintage effect accounted for 0.10 points.

Hulten (1992) employed a second approach, measuring capital not in physical units, but in efficiency units. Using data on quality-adjusted investment flows of capital goods purchased by manufacturing industries, he estimated that about 20% of total quality-adjusted technical change in U.S. manufacturing over the period 1949–1983 could be ascribed to embodied technical change in machinery and equipment. However, he found very little difference in the contribution of embodied technical change to total technical change between the periods 1949–1973 and 1974–1983, the slowdown period. Nonetheless, Hulten's methodology is powerful. Correct accounting for units of capital reveals the vintage effect on total factor productivity (TFP) growth explicitly, as our paper will show.

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[1] We will estimate rates of obsolescence for physical capital; for knowledge capital see Bosworth (1978) and Pakes and Schankerman (1984). As Ben Eden pointed out to one of us, this is an aggregation issue. Indeed, we will estimate the stock of capital in efficiency units. For a recent review of capital measurement, see Diewert and Lawrence (2000).

Third, Hulten and Wykoff (1992) used the price of used capital goods to estimate the obsolescence rate of capital. These estimates were based on used asset prices for numerous individual asset classes. Based on these estimates, the economists inferred rates of depreciation for all asset classes in the U.S. Another natural source of information is scrapping data, as we will discuss later.

A fourth approach is exemplified by Harper (2002), who proposed a new technique for estimating the vintage effect based on the contemporaneous marginal product of each asset. His measure of quality adjustment assumes that durable goods prices reflect marginal products—in contradistinction to the standard neoclassical assumption that prices reflect the discounted stream of future rents. Harper used his model to develop a new method of aggregating different vintages of capital.

A fifth approach was used by Wolff (1991, 1996). Using Nelson's method for econometrically estimating the vintage effect (see below), Wolff (1991) found a very significant vintage effect, estimated by the change in the average age of the capital stock, for Canada, France, Germany, Japan, Italy, the U.K., and the U.S. over the period 1880–1979. These results suggested that embodied technical change played a significant role in the productivity fall-off of the 1970s. Using more recent data for these countries, Wolff (1996) estimated that the vintage effect explained on average about two-fifths of the post-1973 productivity slowdown among these countries.

We make interrelated contributions to the theory and the empirics of the vintage effect. Three propositions show that Nelson's (1964) formula for the capital stock (in efficiency units) as a function of age is only an approximation and offer exact formulas, one for the aging of capital as a function of the investment ratio and one for the vintage effect on TFP-growth. We estimate rates of obsolescence using age-of-capital data and the consequent vintage effect in TFP.

One has to be careful. Obsolescence and depreciation are hard to distinguish (Hulten and Wykoff, 1992) and depreciation rates may be used to construct age data. Indeed, our theory will confirm that only combined rates of depreciation and obsolescence feature in the measurement of the (efficiency units) stock and the economic lifetime of capital. The major question is whether our age data of the Bureau of Economic Analysis (BEA) contain independent information. Now according to the BEA's technical documentation, estimates of the age of capital are based on estimated lifetimes of each type of capital and, as a result, do not directly capture expected obsolescence of the capital. In the past BEA used information on scrapping to produce estimates of what it called "gross capital" and "discards" (see Katz and Herman, 1997). In the new *net* capital stock data used here, BEA no longer directly uses scrapping information to obtain its depreciation estimates but it still uses information on scrapping indirectly in its service life estimates.[2] We exploit this source to estimate rates of obsolescence. The remainder of the paper is organized as follows. Section 2 provides some theoretical background on the measurement of the vintage effect, including Nelson's formula. Section 3 introduces our model of the vintage effect and Section 4 provides a theoretical discussion of the relationship between the age of capital

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[2] The depreciation schedule used for each asset reflects, in part, the assumed service life of the asset. The service life estimates in the new BEA capital stock series are, with a few exceptions, unchanged from the older BEA capital stock data. These, in turn, are based on discard data (see Katz and Herman, 1997, p. 74).

and investment. Sections 5–7 provide estimates of the obsolescence rate of capital by type of capital, vintage-adjusted net capital stock, and the vintage effect on TFP-growth for the U.S. Economy over the 1947–1997 period. Concluding remarks are made in Section 8.

2. Background on the vintage effect

The age structure of capital plays an important role in the measurement of productivity. When investment is low, the stock of capital ages and, therefore, the units not only perish, but also become obsolete from a technological point of view: capital is no longer state of the art. This mechanism has a negative contribution to measured productivity; in the absence of technical change, the Solow residual will be negative. Such an outcome is paradoxical, because the residual has been claimed to account for the shift of the production possibilities frontier (Solow, 1957) and knowledge does not contract, but expands.

At least conceptually, the paradox is resolved when capital is measured not in physical units, but in efficiency units (Hulten, 1992). Then, continuing our discussion of the low investment example, the higher obsolescence of capital will show up in a negative contribution to the growth of capital in terms of efficiency units. Since the Solow residual measure of productivity is the difference between the output growth rate and a weighted average of the labor and capital growth rates, the lower measure of capital growth (as capital is measured in efficiency units) yields more productivity. In other words, the conventional measure of productivity would understate the role of technical change in times of an aging stock of capital.

The econometric analysis of the vintage effect in productivity measurement goes back to Nelson (1964). Suppose that this year's capital investment is $s\%$ more productive than last year's, with the obsolescence parameter s constant over time. As Erwin Diewert noted, obsolescence could be interpreted as anticipated price decline, i.e., the expected inflation rate of a new asset is negative. Denote the capital stock measured in natural units (constant prices) by K, and the capital stock in "efficiency units" by K^s. The greater the obsolescence parameter, the smaller will be the capital stock in efficiency units. In other words, K^s will be decreasing in s. In fact, Nelson (1964) has postulated

$$K^s = K \exp(-s\bar{A}) \tag{1}$$

where $\bar{A}$ is the average age of the capital stock. This formula simply states that the capital stock existing at time t is, on average, less efficient by a factor of $s\bar{A}$ than the capital goods produced at time t. One of the contributions of this paper is that the Nelson (1964) specification is shown to be an approximation at best (for small values of $s\bar{A}$) and improvable by a full fledged vintage analysis. Since Wolff (1996) employed the formula, his ascription of the productivity slowdown to the vintage effect should be reinvestigated. This paper sets up a rigorous framework of vintage capital that is amenable to estimation.

Although the functional form used in formula (1) will be shown to be untenable, the fact that a higher rate of obsolescence effectively diminishes the volume of capital is true and has a simple implication for the measurement of productivity. The explanation begins with a general definition of TFP-growth by means of a Solow residual that features an arbitrary obsolescence parameter, s:

$$\mathrm{TFP}^{s\wedge} = \hat{Y} - \alpha L^{\wedge} - \beta K^{s\wedge} \tag{2}$$

where $\hat{Y} = (p\,\mathrm{d}y/\mathrm{d}t)/py$ (with p the commodity price vector and y the net output vector), $\alpha = wL/py$ (with w the wage rate and L labor employment), $L^{\hat{}} = (\mathrm{d}L/\mathrm{d}t)/L$, $\beta = rK^s/py$ (with r the rental rate of capital).

When capital obsolescence is ignored, $s = 0$, $K^s = K$, and $\mathrm{TFP}^{s\hat{}} = \mathrm{TFP}^{\hat{}}$. Otherwise, measured productivity growth is corrected. A result of this paper is that the correction must be upward (downward) if capital ages (becomes younger). The measurement of capital in terms of efficiency units and the consequent adjustment of measured productivity require an estimate of the obsolescence parameter, s. This will be obtained by an analysis of age data.[3]

3. The model

Consider a unit of investment at time t, the *vintage* of this piece of capital, and the stream of services that it will yield at later times $t' > t$. The initial level of the capital service is $\exp(st)$, where s is the obsolescence parameter; future capital is more productive. Thereafter, for $t' > t$, depreciation takes its toll at a rate σ and the level of capital service goes down to $\exp(st)\exp[-\sigma(t' - t)]$, where σ is the depreciation parameter. We assume that the obsolescence and depreciation parameters are constant over time, but may vary by *type of capital*.

The exponential decay of capital is the most common specification and the depreciation parameter admits an easy interpretation in terms of lifetime. For illustration consider a unit of investment at time 0. It yields a stream of capital services $\exp(-\sigma t)$ at times $t > 0$. What is the expected lifetime? At time t the amount of capital that depreciates is $-\mathrm{d}/\mathrm{d}t\,\exp(-\sigma t) = \sigma\exp(-\sigma t)$. This density function sums to unity over $t > 0$. The expected lifetime is

$$\int t\,\sigma\,\exp(-\sigma t)\,\mathrm{d}t = \frac{1}{\sigma}\int t\,\sigma\,\exp(-\sigma t)\,\mathrm{d}\sigma t = \frac{1}{\sigma} \tag{3}$$

Here $\int$ is the integral from 0 to ∞. *This notation holds throughout this paper*. Expression (3) shows that a rate of depreciation of for example 5% implies a lifetime of 20 years.

Change the perspective by looking backward from time t. Let I denote investment. In natural units (constant prices), the stock of capital at time t is

$$K(t) = \int I(t - t')\,\exp(-\sigma t')\,\mathrm{d}t' \tag{4}$$

Depreciation (at the rate σ) refers to the *physical deterioration* of capital goods. For example, internal combustion engines lose efficiency over time as fissures develop between the piston and cylinder.[4] Obsolescence, on the contrary, refers to *economic deterioration*. For example, a matrix printer may still function well, but now it pales in comparison to a laser printer.[5]

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[3] For other vintage models, see Böhm-Bawerk (1959), Tatom (1979), Wolff (1991), or Abramovitz (1994).

[4] Another example is a baseball pitcher, whose throwing speed will generally decline as he ages.

[5] An obsolescence rate may be negative. First class train service is not what it used to be.

In current efficiency units, invoking obsolescence parameter s, the stock of capital at time t is

$$K^s(t) = \int I(t-t')\exp(-st')\exp(-\sigma t')\,\mathrm{d}t' \tag{5}$$

Equation (5) shows that in terms of efficiency units only the combined rate of depreciation and obsolescence matters, that is $s+\sigma$. As equation (3) showed that the physical lifetime of capital is $1/\sigma$, the economic lifetime is only $1/(s+\sigma)$. Differentiating with respect to t and integrating by parts,

$$\frac{\mathrm{d}K^s}{\mathrm{d}t} = I - (s+\sigma)K^s \tag{6}$$

Substituting (6) into (2),

$$\mathrm{TFP}^{s\wedge} = \hat{Y} - \alpha L^{\wedge} - \beta\left[\frac{I}{K^s} - (s+\sigma)\right] \tag{7}$$

where K^s is given by (5) and also features s in combination with σ only. Formula (7) shows that TFP-growth equals net output growth minus labor growth, minus the investment rate, and minus the sum of obsolescence and depreciation. From an economic point of view, it does not matter if capital deteriorates because of physical or technological aging—that is depreciation (σ) or obsolescence (s). Empirically, the obsolescence parameter is hard to get. For this purpose we will analyze age data.

Suppose we invested one unit of capital last year and one unit this year. The average age of the stock of capital is less than 0.5, because last year's unit has depreciated. For example, if the rate of depreciation is 10%, we have 0.9 unit of last year and 1 unit of this year, so that the average age is 0.45. In terms of efficiency units, the average age is even less. For example, if the rate of obsolescence is also 10%, the average goes down to 0.40. Obviously, the average age of the stock depends on the rate of obsolescence we employ. Formally, it is defined by

$$\bar{A}^s(t) = \frac{\int I(t-t')\exp[-(s+\sigma)t']t'\,\mathrm{d}t'}{\int I(t-t')\exp[-(s+\sigma)t']\,\mathrm{d}t'} \tag{8}$$

The numerator accounts for each unit of capital by its age, t', and the denominator is the total number of units, or $K^s(t)$ of (4). When capital obsolescence is ignored, $s=0$ and $\bar{A}s(t) = \bar{A}(t)$. An important question is whether the average age of capital has risen or lessened over time. The answer depends on the time derivative of (8), which is presented in the next section.

4. The relationship between the age of capital and investment

Investment adds young units to the stock of capital. It contributes to the age reduction of capital. On the other hand, there is the autonomous aging of capital. To beat this, investment must be strong enough to lower the average age of capital. The change in the age of capital is given by the following proposition:

Proposition 1.

$$\frac{\mathrm{d}\bar{A}^s}{\mathrm{d}t} = 1 - \left(\frac{I}{K^s}\right)\bar{A}^s.$$

Proof. The derivative of the numerator of (8) becomes, integrating by parts, $\int I(t-t')\{\exp[-(s+\sigma)t'] - (s+\sigma)\exp[-(s+\sigma)t']t'\}\,\mathrm{d}t' = K^s(t)[1-(s+\sigma)\bar{A}^s(t)]$. The derivative of the denominator of (8) is given by (6). It follows, by the quotient rule and the fact that the numerator can be written as $\bar{A}^s(t)K^s(t)$ in view of (8) and (5), that $\mathrm{d}\bar{A}^s(t)/\mathrm{d}t = \{K^s(t)\cdot K^s(t)[1-(s+\sigma)\bar{A}^s(t)] - \bar{A}^s(t)K^s(t)[I(t)-(s+\sigma)K^s(t)]\}/K^s(t)^2$. This simplifies into $1-[I(t)/K^s(t)]\bar{A}^s(t)$. □

An alternative proof, in discrete time, has been given to us by Erwin Diewert and is presented in Appendix B. Proposition 1 is quite intuitive. It states that if the investment ratio is the inverse of the age of capital, then the age will be preserved. If the investment ratio is higher (lower) than the inverse of the age of capital, then capital will become younger (older). Though intuitive, Proposition 1 has an important ramification.

Proposition 2. *Formula (1) is not exact.*

Proof. Suppose (1) is exact. Differentiation with respect to time yields, $\mathrm{d}K^s/\mathrm{d}t = \mathrm{d}K/\mathrm{d}t\cdot\exp(-s\bar{A}) - K\cdot s\exp(-s\bar{A})\cdot\mathrm{d}\bar{A}/\mathrm{d}t$. By (6) and (1), the left hand side is $I-(s+\sigma)K^s = I-(s+\sigma)K\cdot\exp(-s\bar{A})$. Multiplying through by $\exp(s\bar{A})$ we obtain $\exp(s\bar{A})\cdot I-(s+\sigma)K = \mathrm{d}K/\mathrm{d}t - K\cdot s\cdot\mathrm{d}\bar{A}/\mathrm{d}t$. On the right hand side, using (6) with $s=0$, the first term is $I-\sigma K$ and, using Proposition 1 with $s=0$, the second term is $-K\cdot s\cdot[1-(I/K)\bar{A}]$. The terms sK and σK cancel, respectively. Dividing by I we obtain $\exp(s\bar{A}) = 1+s\bar{A}$. This non-linear equation is approximately true for small values of $s\bar{A}$, but exact only for $s\bar{A}=0$. □

The upshot of Proposition 1 is that simple replacement of $K(t)$ by $K^s(t)$ on a yearly basis amounts to an approximate modification of TFP-growth for obsolescence (s) at best. A more exact procedure reconstructs $K^s(t)$ on the basis of past investment.

5. Estimation of obsolescence and of the growth in the capital stock

Instead of using Nelson's formula (1) in a regression analysis (Wolff, 1996), we will go back to basics—namely equation (8), the definition of capital age. Since we assume that the obsolescence and depreciation parameters are constant over time, the equation cannot exactly meet the data and, therefore, we must attach an error term:[6]

$$\bar{A}^s(t) = \frac{\int I(t-t')\exp[-(s+\sigma)t']t'\,\mathrm{d}t'}{\int I(t-t')\exp[-(s+\sigma)t']\,\mathrm{d}t'} + \varepsilon_t(s+\sigma) \tag{9}$$

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[6] Robert Inklaar has suggested that the rate of obsolescence has accelerated and could be made period specific.

On the left hand side we enter the Bureau of Economic Analysis' age of capital (by type of capital) and implicitly assume that the weights of vintages are in terms of efficiency units.[7] There are 57 types of capital goods (see Table 1 for a listing) and the series runs from 1947 to 1997.[8] We use annual time-series data, so that we effectively replace the integral in equation (9) with a sum.

On the right hand side, we enter investment data. These are also obtained from the Bureau of Economic Analysis fixed reproducible capital series. There are also 57 types of investment goods (corresponding to the 57 capital types) and the series runs from 1901 to 1997. Since the right hand side features the expression $s+\sigma$, the error term will depend on the sum, as indicated in equation (9). Now let $\varepsilon_t(s+\sigma)$ have density function f with mean zero and unknown variance. The likelihood of our observations is the product $\ldots \cdot f[\varepsilon_t(s+\sigma)] \cdot \ldots \cdot f[\varepsilon_0(s+\sigma)]$. Maximization of the log likelihood, which is a series, yields an estimate of $s+\sigma$. If the error term is normally distributed, estimation via non-linear least squares (NLLS) is equivalent to maximum likelihood estimation, so in that case NLLS will provide consistent and asymptotically efficient estimates (Amemiya, 1985).

Equation (9) was estimated using NLLS, with a separate regression performed for each capital type to arrive at type-specific rates of obsolescence and depreciation. The results are shown in Table 1. In light of the rapid rate of technological innovation in the computer industry, it is no surprise that the rates of obsolescence and depreciation are highest for computer-related equipment. The estimates suggest that, on average, more than half (0.521) of the efficiency units of mainframe computers and computer tape drives was lost each year during the period to obsolescence and depreciation, with the rates for computer storage devices (0.457) and computer printers (0.452) only somewhat slower. The personal computers rate of obsolescence and depreciation, 0.256, is equivalent to a lifetime of 4 years, see equation (3).[9] To put these rates in perspective, an annual rate of obsolescence and depreciation of 0.067 is obtained if one restricts this parameter to be the same for all capital types combined. On the other end of the spectrum are buildings and other structures, which tend to have longer lives than other types of capital. For example, the combined rate of depreciation and obsolescence for commercial warehouses is 0.023, that for amusement and recreational buildings is 0.025, and that for hospitals and other institutional buildings is only 0.019. In the middle is a variety of industrial, transportation, and miscellaneous equipment, such as aircraft (0.103), agricultural machinery (0.115), and construction machinery (0.051).

We next compare rates of growth of our newly estimated net stocks of capital with those of the BEA both by type of capital and by industry. It should be noted that while the BEA does adjust capital stock each year for depreciation, it does not generally adjust the capital stock figures for technological obsolescence. The major exception is computer equipment, which is adjusted each year on the basis of a hedonic regression that captures

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[7] The Bureau of Economic Analysis does not disentangle annual rings of capital and, therefore, we cannot test this implicit assumption. As Nelson (1964, footnote 13) points out, the issue is the measurement of capital in physical versus value terms. Our inclusion of the obsolescence effect is tantamount to assuming that values are used for the weights in the capital age calculation. This seems reasonable.

[8] The source is: U.S. Bureau of Economic Analysis, CD-ROM NCN-0229, "Fixed Reproducible Tangible Wealth of the United States, 1925–1997."

[9] According to Elsa Fontainha this agrees with the accounting rules, at least in Portugal.

Table 1
Rates of obsolescence and depreciation by capital type

	Capital type	Parameter	Standard error	*t*-Statistic
1.	Mainframe computers	0.521	0.005	99.1
2.	Personal computers	0.256	0.005	54.5
3.	Direct access storage devices	0.176	0.024	7.5
4.	Computer printers	0.452	0.007	63.7
5.	Computer terminals	0.355	0.007	53.0
6.	Computer tape drives	0.521	0.147	3.6
7.	Computer storage devices	0.457	0.005	87.4
8.	Other office equipment	0.340	0.003	124.5
9.	Communication equipment	0.116	0.001	101.5
10.	Instruments	0.140	0.001	106.1
11.	Photocopy and related equipment	0.195	0.001	144.0
12.	Nuclear fuel rods	0.413	0.000	[a]
13.	Other fabricated metal products	0.091	0.001	123.6
14.	Steam engines	0.050	0.001	71.3
15.	Internal combustion engines	0.222	0.007	30.5
16.	Metalworking machinery	0.119	0.003	37.6
17.	Special industry machinery, n.e.c.	0.100	0.003	33.8
18.	General industrial, including materials handling, equipment	0.107	0.003	42.9
19.	Electrical transmission, distribution, and industrial apparatus	0.049	0.000	126.6
20.	Trucks, buses, and truck trailers	0.205	0.003	68.7
21.	Autos	0.192	0.006	32.5
22.	Aircraft	0.103	0.002	47.8
23.	Ships and boats	0.059	0.002	32.1
24.	Railroad equipment	0.060	0.002	25.5
25.	Household furniture	0.145	0.002	64.7
26.	Other furniture	0.127	0.001	182.1
27.	Farm tractors	0.155	0.002	78.0
28.	Construction tractors	0.180	0.002	112.2
29.	Agricultural machinery, except tractors	0.115	0.003	37.9
30.	Construction machinery, except tractors	0.151	0.003	43.3
31.	Mining and oilfield machinery	0.159	0.001	161.8
32.	Service industry machinery	0.166	0.001	115.2
33.	Household appliances	0.175	0.003	62.6
34.	Other electrical equipment, n.e.c.	0.195	0.002	128.6
35.	Other non-residential equipment	0.156	0.001	122.3
36.	Industrial buildings	0.031	0.001	49.2
37.	Office buildings	0.023	0.002	13.5
38.	Mobile structures	0.060	0.004	16.2
39.	Commercial warehouses	0.023	0.002	15.5
40.	Other commercial buildings, n.e.c.	0.026	0.001	18.7
41.	Religious buildings	[b]	[b]	[b]
42.	Educational buildings	0.188	0.216	0.9
43.	Hospital and institutional buildings	0.019	0.001	13.6
44.	Hotels and motels	0.035	0.007	5.0
45.	Amusement and recreational buildings	0.025	0.004	5.7
46.	Other non-farm buildings	0.024	0.001	22.7
47.	Local transit buildings	[b]	[b]	[b]
48.	Railroad structures	−0.004	0.000	[a]
49.	Railroad track replacement	0.021	0.000	[a]
50.	Telecommunications	[b]	[b]	[b]

Table 1 (*Continued*)

	Capital type	Parameter	Standard error	*t*-Statistic
51.	Electric light and power	0.022	0.000	[a]
52.	Gas	0.023	0.000	[a]
53.	Petroleum pipelines	0.020	0.000	[a]
54.	Farm-related buildings and structures	0.016	0.003	6.2
55.	Petroleum and natural gas exploration	0.057	0.000	[a]
56.	Other mining exploration	0.044	0.001	76.4
57.	Other non-farm structures	0.016	0.002	6.9

[a] Standard error is zero (capital type has only one observation), so *t*-statistic cannot be computed.

[b] Estimation did not converge. We do not adjust the BEA stocks.

such features of computers as speed and memory. The comparisons are shown in Tables 2 and 3.

Table 2 shows the annualized growth rates of net capital stock by capital type. We have aggregated the types from the original 57 to 28 because many of the series have zeroes in the early years of the period (for example, computer equipment and nuclear fuel rods). If the vintage parameter s is positive, then a rising ratio of investment to net capital stock over a period will cause the vintage-adjusted capital growth rate to exceed the BEA capital growth rate. Conversely, if the investment to net capital stock ratio is declining over a period (and s is positive), then the vintage-adjusted capital growth rate will be less than the BEA capital growth rate.

Over the full 1947–1997 period, there was very little difference between the BEA and the vintage-adjusted growth rate of the total capital stock—only 0.09 percentage points. Differences are quite small for most of the capital types. There are a few exceptions. The vintage-adjusted annual growth rate of other office equipment exceeded the BEA growth rate by 0.36 percentage points, as did the vintage-adjusted growth rate of petroleum and natural gas exploration equipment. In contrast, the annual growth rate of the BEA net stock of automobiles exceeded the vintage-adjusted growth rate by 1.04 percentage points. The last line of the table shows the correlation coefficient between the two sets of growth rates across the 28 capital types. Over the full 1947–1997 period, the correlation is extremely high (0.99).

Results also vary by 10-year period. The vintage-adjusted annual growth rate for total capital exceeded the BEA growth rate by 0.39 percentage points in the 1947–1957 period and by 0.10 percentage points in the 1957–1967 period but fell short of it by 0.10 percentage points in the 1987–1997 period. The biggest differences are recorded for computer equipment. In the 1967–1977 period, the difference between the BEA and the vintage-adjusted growth rate (2.70 percentage points) was a reflection of the rapid acceleration in computer equipment investment over the period. The difference was −1.99 percentage points in the 1977–1987 period, but virtually zero in the 1987–1997 period. Other large differences in the two growth rates are observed for autos as well as railroad structures and track. However, by and large, the correlation in the two sets of capital growth rates is very high by 10-year period—ranging from 0.983 to 0.998.

The BEA capital stock data are also available for 62 individual industries (see Table A.1 for a listing). In Table 3, we show the results for 11 major sectors. Differences in the

Table 2

Annual rate of growth of net capital stock by capital type and period, 1947–1997 (figures are in percentage points)

Capital type[a]	1947–1997			1947–1957			1957–1967			1967–1977			1977–1987			1987–1997		
	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.
Computer equipment (1–7)	–	–	–	–	–	–	–	–	–	26.39	29.08	−2.70	30.69	32.68	−1.99	21.22	21.18	0.05
Other office equipment (8 and 11)	7.01	7.37	−0.36	7.87	8.96	−1.09	7.02	7.52	−0.50	10.03	10.30	−0.27	8.20	8.10	0.10	1.94	1.98	−0.04
Communication equipment (9)	8.08	8.11	−0.03	10.15	10.13	0.02	9.62	9.63	0.00	7.32	7.33	−0.02	8.69	8.70	−0.01	4.64	4.76	−0.13
Instruments (10)	6.24	6.28	−0.04	10.43	10.48	−0.04	2.50	2.55	−0.05	7.96	7.92	0.04	5.82	5.84	−0.02	4.48	4.60	−0.13
Fabricated metal products (12 and 13)	3.60	3.68	−0.08	7.12	7.17	−0.05	2.58	2.65	−0.08	7.17	7.15	0.01	1.08	1.25	−0.16	0.07	0.18	−0.11
Engines and industrial machinery (14–19)	3.32	3.43	−0.11	5.18	5.40	−0.22	3.70	3.80	−0.10	3.37	3.45	−0.08	2.35	2.36	−0.01	2.01	2.15	−0.14
Trucks, buses, and truck trailers (20)	4.48	4.42	0.05	4.98	4.66	0.32	4.84	4.89	−0.05	5.92	6.12	−0.20	2.27	2.08	0.19	4.37	4.36	0.01
Autos (21)	5.12	4.08	1.04	9.61	7.42	2.19	2.66	0.40	2.26	5.65	7.49	−1.84	4.49	4.09	0.40	3.18	1.00	2.18
Aircraft (22)	6.68	6.36	0.32	7.70	7.51	0.18	13.66	13.17	0.48	6.63	5.96	0.67	3.53	3.35	0.18	1.89	1.83	0.06
Ships and boats (23)	1.10	1.02	0.08	1.14	0.84	0.30	1.29	1.03	0.26	5.01	4.88	0.13	0.58	0.65	−0.07	−2.54	−2.31	−0.22
Railroad equipment (24)	0.46	0.38	0.07	2.49	2.59	−0.10	0.31	0.33	−0.02	1.00	1.04	−0.04	−1.39	−1.34	−0.05	−0.13	−0.72	0.58
Furniture (25 and 26)	4.37	4.38	−0.01	4.69	4.85	−0.16	4.10	4.08	0.02	3.27	3.21	0.06	5.84	5.84	0.00	3.96	3.94	0.02
Agricultural, construction, mining, and service industry machinery (27–32)	2.55	2.67	−0.12	5.61	6.03	−0.42	2.61	2.65	−0.05	4.63	4.55	0.08	−0.30	−0.23	−0.07	0.22	0.37	−0.14
Appliances and other equipment (33–35)	5.77	5.86	−0.09	5.39	5.77	−0.38	7.34	7.38	−0.04	6.76	6.77	−0.01	5.70	5.72	−0.02	3.67	3.69	−0.02
Industrial and commercial buildings (36–40)	3.46	3.67	−0.21	2.78	3.23	−0.45	4.37	4.65	−0.28	3.80	3.95	−0.15	4.07	4.15	−0.09	2.29	2.39	−0.10
Educational and institutional buildings (41–43)	4.06	4.29	−0.24	5.45	6.00	−0.55	5.95	6.19	−0.24	3.56	3.56	0.00	2.65	3.02	−0.37	2.67	2.70	−0.03
Hotels and motels (44)	4.37	4.43	−0.07	2.11	2.14	−0.04	7.63	8.02	−0.39	3.80	3.71	0.09	5.10	5.19	−0.09	3.19	3.10	0.09
Recreational buildings (45)	1.91	2.01	−0.10	0.79	1.06	−0.27	3.84	3.81	0.03	1.01	1.20	−0.20	1.22	1.35	−0.13	2.67	2.63	0.04
Other non-farm buildings (46)	2.39	2.73	−0.34	3.24	4.05	−0.81	6.74	7.30	−0.55	−0.25	−0.31	0.06	1.58	1.76	−0.18	0.65	0.87	−0.22
Local transit buildings (47)	−2.47	−2.47	0.00	−1.89	−1.89	0.00	−3.16	−3.16	0.00	−2.46	−2.46	0.00	−2.43	−2.43	0.00	−2.43	−2.43	0.00
Railroad structures and track (48 and 49)	−0.87	0.34	−1.20	−0.69	0.68	−1.36	−1.19	0.13	−1.32	−0.91	0.29	−1.20	−0.67	0.39	−1.06	−0.89	0.20	−1.08
Telecommunications (50)	4.08	4.08	0.00	4.94	4.94	0.00	4.27	4.27	0.00	5.07	5.07	0.00	3.93	3.93	0.00	2.19	2.19	0.00

Table 2 (*Continued*)

Capital type[a]	1947–1997			1947–1957			1957–1967			1967–1977			1977–1987			1987–1997		
	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.
Electric light and power and gas (51 and 52)	2.68	2.67	0.01	4.78	4.82	−0.04	2.99	2.97	0.02	3.11	3.12	−0.01	1.76	1.72	0.04	0.74	0.71	0.03
Petroleum pipelines (53)	0.78	1.23	−0.45	1.29	2.01	−0.72	0.11	0.63	−0.53	3.76	4.13	−0.37	−0.83	−0.47	−0.36	−0.45	−0.17	−0.28
Farm-related buildings and structures (54)	2.08	1.90	0.18	3.32	3.31	0.00	3.47	2.91	0.56	3.68	2.56	1.12	0.50	0.99	−0.50	−0.59	−0.29	−0.30
Petroleum and gas exploration (55)	2.62	2.98	−0.36	6.26	6.27	−0.01	2.42	2.45	−0.03	1.41	1.57	−0.16	4.20	4.92	−0.73	−1.21	−0.34	−0.87
Other mining exploration (56)	3.14	3.15	−0.01	1.61	1.65	−0.04	3.27	3.25	0.02	6.55	6.47	0.08	4.12	4.16	−0.03	0.15	0.23	−0.08
Other non-farm structures (57)	2.66	2.93	−0.28	−0.53	0.11	−0.64	1.71	2.13	−0.42	3.63	3.75	−0.12	4.67	4.75	−0.08	3.80	3.92	−0.12
Total	3.05	3.13	−0.09	3.13	3.51	−0.39	3.21	3.30	−0.10	3.44	3.45	−0.01	2.99	3.02	−0.04	2.48	2.38	0.10
Correlation between BEA and vintage growth rates[b]			0.989			0.983			0.985			0.994			0.998			0.992

Note: BEA figures are for non-residential net stocks, real-cost valuation (1992 Dollars). Governmental capital stock is excluded.

[a] The numbers in parentheses refer to the capital type classification scheme in Table 1.

[b] Computer equipment is excluded because of zero values for the computation of correlation coefficients for 1947–1997, 1947–1957, and 1957–1997.

Table 3

Annual rate of growth of net capital stock by major sector and period, 1947–1997 (figures are in percentage points)

Sector[a]	1947–1997			1947–1957			1957–1967			1967–1977			1977–1987			1987–1997		
	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.
Agriculture (1 and 2)	2.15	2.08	0.08	4.23	4.11	0.12	2.87	2.59	0.28	4.01	3.37	0.64	−0.44	−0.04	−0.40	0.09	0.35	−0.27
Mining (3–6)	2.63	2.88	-0.25	4.82	4.92	-0.09	3.03	3.07	−0.04	2.14	2.26	−0.12	4.22	4.63	−0.41	−1.07	−0.47	−0.60
Construction (7)	2.33	2.53	−0.19	4.10	4.85	−0.74	3.52	3.53	−0.01	4.30	4.21	0.09	−0.41	−0.40	−0.02	0.16	0.44	−0.28
Manufacturing non-durables (19–28)	2.56	2.62	−0.06	2.58	2.75	−0.17	2.97	3.07	−0.10	3.61	3.70	−0.10	1.66	1.67	−0.01	1.96	1.91	0.05
Manufacturing durables (8–18)	3.02	3.25	−0.24	4.37	5.00	−0.63	3.59	3.85	−0.26	3.37	3.56	−0.19	2.14	2.19	−0.04	1.61	1.67	−0.06
Transportation (29–35)	0.23	0.79	−0.56	0.05	0.99	−0.93	−0.24	0.53	−0.77	0.71	1.15	−0.44	0.25	0.65	−0.40	0.36	0.64	−0.28
Communications (36 and 37)	5.56	5.55	0.01	7.07	7.02	0.05	6.07	6.04	0.02	5.96	6.01	−0.05	5.10	5.11	0.00	3.60	3.55	0.04
Utilities (38–40)	3.18	3.27	−0.09	5.24	5.51	−0.28	3.16	3.24	−0.08	3.61	3.69	−0.09	2.68	2.69	0.00	1.22	1.23	−0.01
Trade (41 and 42)	4.51	4.44	0.06	3.44	3.32	0.12	5.15	5.10	0.04	4.47	4.62	−0.15	4.87	4.79	0.08	4.60	4.38	0.22
Finance, insurance, and real estate (43–49)	4.55	4.78	−0.23	4.16	4.68	−0.52	5.50	5.76	−0.26	4.00	4.09	−0.10	5.25	5.62	−0.37	3.82	3.73	0.09
Other services[b] (50–62)	5.21	5.08	0.13	5.82	5.81	0.00	6.50	6.43	0.07	5.20	5.12	0.09	3.56	3.41	0.15	4.96	4.64	0.32
Total	3.05	3.13	−0.09	3.13	3.51	−0.39	3.21	3.30	−0.10	3.44	3.45	−0.01	2.99	3.02	−0.04	2.48	2.38	0.10
Correlation of growth rates across 62 industries (scalar)		0.952			0.973			0.887			0.941			0.987			0.989	

Note: BEA figures are for non-residential net stocks, real-cost valuation (1992 Dollars).

[a] The numbers in parentheses refer to the industry classification scheme shown in Appendix A.

[b] Non-governmental services only.

annual growth rates of the two capital stock series over the full 1947–1997 period are relatively small for the total capital stock and for most sectors, with the notable exception of transportation, with a difference of 0.56 percentage points between the vintage-adjusted and the BEA series. The correlation in capital growth rates over the 1947–1997 period across the 62 individual industries is 0.95, somewhat lower than the correlation coefficient across capital types.

Differences in capital growth rates between the two series are more marked for the individual 10-year periods than for the full 50-year period. In the 1947–1957 period, large differences are found for durables manufacturing, transportation, and the combined sector, fire, insurance, and real estate; in the 1957–1967 period, for transportation; in the 1967–1977 period, for both agriculture and transportation; in the 1977–1987 period, for agriculture, mining, transportation, and finance, insurance, and real estate; and in the 1987–1997 period, for mining.[10]

6. Estimation of implied TFP-growth

Substitution of our estimate of the total obsolescence and depreciation rate in formula (7) yields TFP-growth corrected for vintage effects. Estimates of TFP-growth based on BEA capital and on efficiency units (that is, vintage-adjusted capital stock) are shown in Table 4 for the major sectors and the total non-governmental economy. The output measure is real gross domestic product in chained 1992 Dollars; the labor input is persons engaged in production (PEP); the capital input is non-residential net stocks, real-cost valuation (1992 Dollars); and the labor share is the ratio of employee compensation to net national product.[11] Due to differences in industry classification between the two sources, we use 58 industries instead of 62 (see Table 5).

Over the full 1947–1997 period, overall TFP grew slightly faster (0.04 percentage points per year) on the basis of the BEA capital stock data than on the basis of the vintage-adjusted capital stock in efficiency units. This is a reflection of the slightly slower growth in BEA capital stock than capital stock in efficiency units. Differences are also quite small for the 11 major sectors. The largest difference in annual TFP-growth is recorded for the finance, insurance, and real estate sector—a 0.18 percentage points difference between the BEA and the vintage-adjusted measures. The correlation in TFP-growth rates over the 1947–1997 period across the 58 individual industries is 0.90.

Differences in TFP-growth rates between the two series are somewhat more marked for the individual 10-year periods than for the full 50-year period. In the 1947–1957 period, large differences in annual TFP-growth are found for finance, insurance, and real estate (0.39 percentage points), transportation (0.21), construction (0.20), and for the overall economy (0.16); in the 1957–1967 period, for agriculture (−0.21), transportation (0.17), and finance, insurance, and real estate (0.20 percentage points); in the 1967–1977 period, for agriculture (−0.49); in the 1977–1987 period, for agriculture (0.30), mining (0.22), and finance,

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[10] The correlation coefficients in capital growth rates across the 62 industries by ten-year period range from a low of 0.89 in the 1957–1967 period to a high of 0.99 in the 1987–1997 period.

[11] The source for all data except the capital stock data is: http://www.bea.doc.gov/bea/dn2.htm.

Table 4

Annual rate of growth of total factor productivity by major sector and period, 1947–1997 (figures are in percentage points)

Sector	1947–1997			1947–1957			1957–1967			1967–1977			1977–1987			1987–1997		
	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.	BEA	Vintage	Diff.
Agriculture	0.71	0.77	−0.06	−1.70	−1.61	0.09	−1.24	−1.03	−0.21	−1.73	−1.24	−0.49	4.89	4.59	0.30	3.35	3.15	0.20
Mining	1.08	0.95	0.13	1.17	1.12	0.05	2.21	2.19	0.02	−0.58	−0.65	0.06	−1.26	−1.47	0.22	3.86	3.55	0.31
Construction	−0.20	−0.25	0.05	2.84	2.64	0.20	1.12	1.12	0.00	−4.39	−4.36	−0.02	−0.78	−0.78	0.00	0.21	0.14	0.07
Manufacturing non-durables	1.84	1.82	0.02	2.13	2.08	0.05	2.43	2.40	0.03	2.28	2.25	0.03	1.76	1.75	0.00	0.59	0.60	−0.02
Manufacturing durables	2.55	2.51	0.05	1.86	1.74	0.12	2.15	2.10	0.05	1.82	1.78	0.04	2.19	2.18	0.01	4.75	4.74	0.01
Transportation	1.17	1.05	0.13	0.17	−0.04	0.21	2.90	2.73	0.17	1.00	0.90	0.10	0.52	0.43	0.09	1.26	1.20	0.06
Communications	2.54	2.54	−0.01	2.19	2.21	−0.02	3.45	3.46	−0.01	2.85	2.83	0.02	2.45	2.45	0.00	1.73	1.75	−0.02
Utilities	2.74	2.68	0.06	4.60	4.43	0.17	3.57	3.53	0.05	4.08	4.02	0.05	−1.25	−1.25	0.00	2.69	2.69	0.01
Trade	0.74	0.77	−0.03	1.67	1.72	−0.05	1.17	1.19	−0.02	−0.75	−0.81	0.06	0.38	0.41	−0.03	1.24	1.33	−0.09
Finance, insururance, and real estate	−0.29	−0.47	0.18	1.65	1.26	0.39	−0.18	−0.38	0.20	0.06	−0.02	0.07	−1.94	−2.22	0.28	−1.05	−0.99	−0.07
Other services[a]	−0.24	−0.20	−0.04	−0.09	−0.09	0.00	0.26	0.28	−0.02	0.33	0.35	−0.03	−0.56	−0.51	−0.05	−1.14	−1.04	−0.10
Total	1.12	1.08	0.04	1.90	1.74	0.16	1.87	1.83	0.04	0.53	0.52	0.01	0.33	0.31	0.02	0.95	0.99	−0.04
Correlation of growth rates across 58 industries (scalar)		0.898			0.992			0.961			0.992			0.998			0.999	

Note: The output measure is real gross domestic product in chained 1992 Dollars; the labor input is persons engaged in production (PEP); the capital input is non-residential net stocks, real-cost valuation (1992 Dollars), and the labor share is the ratio of employee compensation to net national product.

[a] Non-governmental services only.

Table 5

Annual rate of growth of total factor productivity by industry and period, 1947–1997 (figures are in percentage points)

Industry		BEA Capital stock estimates						Vintage capital stock in efficiency units					
		1947–1967	1967–1987	1987–1997	1967 Slowdown	1987 Recovery	Five period std. dev.	1947–1967	1967–1987	1987–1997	1967 Slowdown	1987 Recovery	Five period std. dev.
1	Farms	1.06	2.59	3.83	1.54	1.24	1.97	1.14	2.64	3.69	1.50	1.05	1.85
2	Agricultural services, forestry, and fishing	−1.55	1.06	0.84	2.61	−0.22	1.95	−1.54	1.12	0.83	2.66	−0.29	1.94
3	Metal mining	2.07	1.80	7.26	−0.27	5.46	4.59	2.01	1.78	7.21	−0.23	5.43	4.58
4	Coal mining	3.30	0.76	9.85	−2.53	9.08	4.59	3.24	0.81	9.78	−2.43	8.97	4.56
5	Oil and gas extraction	0.22	−1.94	2.83	−2.16	4.77	2.25	0.21	−2.15	2.39	−2.36	4.54	2.36
6	Non-metallic minerals, except fuels	2.59	3.17	2.48	0.58	−0.69	0.42	2.48	3.15	2.37	0.67	−0.78	0.46
7	Construction	1.98	−2.58	0.21	−4.56	2.80	2.41	1.88	−2.57	0.14	−4.45	2.71	2.36
8	Lumber and wood products	1.22	2.29	−2.49	1.07	−4.78	2.92	1.15	2.27	−2.49	1.12	−4.76	2.93
9	Furniture and fixtures	3.51	1.89	1.06	−1.62	−0.82	1.74	3.50	1.89	1.06	−1.62	−0.83	1.73
10	Stone, clay, and glass products	1.44	1.45	2.20	0.01	0.76	0.56	1.46	1.46	2.14	0.00	0.68	0.57
11	Primary metal industries	2.79	0.25	2.63	−2.54	2.38	1.81	2.56	0.24	2.62	−2.32	2.39	1.74
12	Fabricated metal products	−1.48	1.71	1.84	3.19	0.13	2.83	−1.45	1.72	1.87	3.17	0.14	2.83
13	Industrial machinery and equipment	1.71	4.10	7.80	2.39	3.70	2.58	1.73	4.09	7.81	2.37	3.72	2.58
14	Electronic and other electric equipment	3.70	2.80	9.90	−0.91	7.10	2.75	3.71	2.79	9.90	−0.92	7.11	2.75
15	Motor vehicles and equipment	3.26	1.96	−0.51	−1.30	−2.47	2.32	3.26	1.94	−0.44	−1.32	−2.38	2.31
16	Other transportation equipment	3.39	0.34	−2.90	−3.04	−3.25	2.51	3.39	0.34	−2.89	−3.05	−3.23	2.52
17	Instruments and related products	2.54	2.63	4.68	0.09	2.05	0.87	2.56	2.64	4.69	0.08	2.05	0.86
18	Miscellaneous manufacturing industries	2.72	2.87	1.03	0.15	−1.84	0.88	2.72	2.86	0.98	0.15	−1.88	0.90
19	Food and kindred products	2.01	2.58	0.17	0.57	−2.41	1.04	1.98	2.56	0.16	0.58	−2.40	1.06
20	Tobacco products	0.57	−5.64	−2.91	−6.21	2.72	4.05	0.71	−5.65	−3.00	−6.36	2.65	4.20
21	Textile mill products	4.18	4.81	2.94	0.63	−1.87	1.22	4.17	4.80	2.93	0.63	−1.87	1.23
22	Apparel and other textile products	1.63	3.20	3.19	1.56	−0.01	0.78	1.63	3.19	3.22	1.55	0.04	0.79
23	Paper and allied products	1.50	2.49	0.70	0.99	−1.80	1.28	1.49	2.48	0.69	0.99	−1.79	1.28
24	Printing and publishing	1.33	−0.21	−1.98	−1.55	−1.77	1.30	1.33	−0.21	−1.95	−1.54	−1.74	1.28
25	Chemicals and allied products	3.89	3.31	1.26	−0.58	−2.05	1.07	3.89	3.29	1.32	−0.60	−1.98	1.06
26	Petroleum and coal products	3.66	2.51	0.01	−1.15	−2.50	2.66	3.51	2.49	−0.01	−1.03	−2.50	2.71
27	Rubber and miscellaneous plastics products	1.23	2.36	3.99	1.12	1.63	1.76	1.22	2.34	4.08	1.12	1.74	1.80
28	Leather and leather products	0.55	2.47	3.66	1.91	1.19	1.46	0.54	2.47	3.65	1.93	1.19	1.47

Table 5 (*Continued*)

Industry		BEA Capital stock estimates						Vintage capital stock in efficiency units					
		1947–1967	1967–1987	1987–1997	1967 Slowdown	1987 Recovery	Five period std. dev.	1947–1967	1967–1987	1987–1997	1967 Slowdown	1987 Recovery	Five period std. dev.
29	Railroad transportation	3.32	2.99	6.46	−0.33	3.47	3.63	3.06	2.76	6.24	−0.29	3.47	3.64
30	Local and interurban passenger transit	−3.82	−1.19	−2.28	2.63	−1.08	1.61	−3.82	−1.15	−2.29	2.67	−1.14	1.62
31	Trucking and warehousing	3.29	−0.27	−0.39	−3.56	−0.12	2.34	3.28	−0.24	−0.25	−3.52	−0.02	2.31
32	Water transportation	−1.25	2.18	0.52	3.44	−1.66	2.04	−1.20	2.18	0.50	3.38	−1.68	2.04
33	Transportation by air	5.66	1.01	1.83	−4.65	0.83	2.96	5.68	1.07	1.79	−4.61	0.72	2.94
34	Pipelines, except natural gas	7.71	2.04	3.24	−5.67	1.20	3.01	7.57	1.97	3.20	−5.61	1.23	2.99
35	Transportation services	0.16	1.13	−0.24	0.97	−1.37	2.41	0.17	1.13	−0.21	0.96	−1.34	2.41
36	Telephone and telegraph	3.00	2.81	2.07	−0.20	−0.74	0.97	3.02	2.80	2.09	−0.22	−0.71	1.02
37	Radio and television	0.55	1.68	0.68	1.13	−1.00	2.54	0.57	1.69	0.74	1.12	−0.95	2.53
38	Electric, gas, and sanitary services	4.08	1.41	2.69	−2.67	1.28	2.09	3.98	1.39	2.69	−2.59	1.30	2.13
39	Wholesale trade	0.68	−0.78	2.07	−1.46	2.85	1.27	0.68	−0.80	2.23	−1.49	3.03	1.36
40	Retail trade	1.47	0.14	0.77	−1.32	0.63	0.69	1.50	0.12	0.80	−1.37	0.68	0.73
41	Banking	−0.70	−1.71	−3.05	−1.01	−1.34	1.04	−0.69	−1.65	−2.86	−0.97	−1.21	1.06
42	Non-depository institutions	1.13	−3.80	−6.04	−4.92	−2.25	3.12	1.31	−3.84	−5.78	−5.15	−1.94	3.30
43	Security and commodity brokers	0.63	0.23	8.65	−0.39	8.42	3.34	0.60	0.26	8.77	−0.34	8.51	3.40
44	Insurance carriers	0.38	−1.94	2.91	−2.33	4.86	3.84	0.40	−1.94	3.00	−2.34	4.94	3.85
45	Insurance agents, brokers, and service	0.86	−1.21	0.22	−2.07	1.43	1.85	0.84	−1.14	0.45	−1.98	1.59	1.90
46	Real estate	1.56	−0.26	0.30	−1.82	0.56	1.00	1.28	−0.41	0.31	−1.69	0.71	0.96
47	Holding and other investment offices	3.13	1.15	−0.45	−1.98	−1.60	2.49	−0.67	−0.56	−0.78	0.11	−0.23	2.36
48	Hotels and other lodging places	0.12	−0.51	2.49	−0.63	3.01	1.94	0.07	−0.50	2.54	−0.57	3.04	1.97
49	Personal services	0.07	−1.00	−0.41	−1.06	0.59	0.51	0.09	−0.98	−0.33	−1.07	0.66	0.65
50	Business services	0.35	−0.48	−0.97	−0.83	−0.49	0.85	0.40	−0.41	−0.89	−0.81	−0.48	0.84
51	Auto repair, services, and parking	−0.65	−0.30	−1.32	0.35	−1.02	1.51	−0.55	−0.26	−1.04	0.29	−0.79	2.11
52	Miscellaneous repair services	−0.36	−0.42	−4.19	−0.07	−3.77	1.68	−0.36	−0.43	−4.27	−0.07	−3.84	1.77
53	Motion pictures	−2.45	1.56	−2.26	4.01	−3.81	2.27	−2.43	1.60	−2.13	4.03	−3.72	2.27
54	Amusement and recreation services	0.88	0.51	−0.04	−0.37	−0.55	1.14	0.85	0.54	0.08	−0.31	−0.46	1.09
55	Health services	−1.11	−0.68	−3.15	0.43	−2.47	1.36	−1.10	−0.69	−3.12	0.41	−2.43	1.41
56	Legal services	−0.50	−2.56	−1.29	−2.05	1.27	2.10	−0.46	−2.50	−1.00	−2.05	1.50	2.07
57	Educational services	−1.04	−1.30	−2.16	−0.26	−0.86	0.96	−1.01	−0.54	−2.03	0.47	−1.49	0.98
58	Other services, n.e.c.	−4.51	2.60	−1.91	7.11	−4.52	4.26	−4.48	2.60	−1.83	7.08	−4.43	4.26
	Total	1.88	0.43	0.95	−1.46	0.52	0.66	1.79	0.42	0.99	−1.37	0.58	0.62

Note: See notes to Table 4 for technical details on TFP estimation. The government sector is not included.

insurance, and real estate (0.28); and in the 1987–1997 period, for agriculture (0.21) and mining (0.31).[12]

7. Aging capital and the vintage effect on TFP

The effect of the incorporation of the rate of obsolescence on TFP-growth is shown to depend on the aging of the stock of capital. In fact, there is a straight proportionality between aging and the vintage effect:

Proposition 3.

$$\frac{\mathrm{dTFP}^{s\wedge}}{\mathrm{d}s} = \frac{\beta \mathrm{d}\bar{A}^s}{\mathrm{d}t}.$$

Proof. Differentiate (7) with respect to s, using (5) and (8): $\mathrm{dTFP}^{s\wedge}/\mathrm{d}s = -\beta\,\mathrm{d}[I/K^s - (s+\sigma)]/\mathrm{d}s = -\beta[-I/K^{s2}(\mathrm{d}/\mathrm{d}s) \int I(t-t')\exp(-st')\exp(-\sigma t')\mathrm{d}t' - 1] = -\beta\,[-I/K^{s2} \int I(t-t')\exp(-st')(-t')\exp(-\sigma t')\mathrm{d}t' - 1] = -\beta[(I/K^s)\bar{A}^s - 1] = \beta\,\mathrm{d}\bar{A}^s/\mathrm{d}t$ by Proposition 1. □

The message of this proposition is clear. In times when capital becomes older, measured TFP-growth increases as obsolescence, s, is taken into account. Conversely, in times when capital becomes younger, measured TFP-growth decreases as obsolescence, s, is taken into account. Thus, the incorporation of obsolescence may well remove some of the cyclicality of TFP-growth. Let us explain.

In an upswing of the business cycle the investment/capital ratio tends to be high. This means, by Proposition 1, that capital becomes younger and, therefore, by Proposition 3, that the incorporation of the vintage effect in TFP measurement amounts to a downward correction. By the same token, in a downswing of the business cycle capital grows older and the incorporation of the vintage effect amounts to an upward correction. In short, the vintage effect is expected to be counter-cyclical.

TFP-growth itself, however, is known to be pro-cyclical, which is considered an awkward finding, as it is supposed to measure the shift of technology rather than the business cycle (see, for example, Gordon, 1979). As the vintage effect is expected to be counter-cyclical, it may have a smoothing impact. In short, the vintage effect may throw light on productivity puzzles such as the pro-cyclical behavior of TFP-growth and the slowdown of productivity in the 1970s.

The results displayed in Table 5 are interesting. The left panel displays standard TFP-growth figures, based on BEA capital stock estimates. The right panel displays our vintage-adjusted TFP-growth rates. In each panel, the first three columns show the annual rate of TFP-growth during the high productivity growth period of 1947–1967, the slow productivity

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[12] The correlation coefficients in capital growth rates across the 58 industries by ten-year period range from a low of 0.96 in the 1957–1967 period to a high of 1.00 in the 1987–1997 period.

growth period of 1967–1987, and then the recovery period 1987–1997.[13] The differences between the figures in the first two columns indicate the 1967 slowdown and are listed in the fourth columns. Similarly, the differences between the figures in the second and third columns indicate the 1987 recovery and are listed in the fifth columns. The sixth and final column in either panel shows the standard deviations of the TFP-growth rates over the five 10-year period (1947–1957, 1957–1967, 1967–1977, 1977–1987, and 1987–1997).

There are three questions of interest. First, does the use of capital measured in efficiency units reduce the measured slowdown between the 1947–1967 and the 1967–1987 periods? Second, does the use of capital in efficiency units increase the measured recovery after 1987 (that is to say, does it cause TFP-growth in the 1987–1997 period to return more closely to its long-term average performance)? Third, does the use of capital in efficiency units reduce disparities in measured TFP-growth across the five 10-year period? The answer to the three questions is generally “yes.”

First, for the overall economy, the slowdown in annual TFP-growth after 1967 is 1.46 percentage points on the basis of BEA capital stock but only 1.37 percentage points on the basis of vintage-adjusted capital stock. The measured slowdown is also reduced in 31 of the 58 detailed industries. Second, for the overall economy, the recovery in annual TFP-growth is 0.52 points on the basis of BEA capital stock and 0.58 points on the basis of capital stock in efficiency units. The measured recovery is also increased in 40 of the 58 detailed industries. Third, the standard deviation of TFP-growth for the overall economy over the five 10-year period is 0.66 on the basis of BEA capital stock and 0.62 on the basis of capital measured in efficiency units. The standard deviation is also lower on the basis of the vintage-adjusted capital stock in 33 of the 58 industries.

8. Conclusion

TFP-growth is known to be pro-cyclical, an awkward finding, as it is supposed to measure the shift of technology rather than the business cycle. If the age of capital is counter-cyclical, then the vintage effect is also counter-cyclical by Proposition 3, a neutralizing effect. In short, the vintage effect throws theoretical light on productivity puzzles such as the slowdown in the 1970s and the pro-cyclicality of productivity growth.

The results indicate that the use of capital stock in efficiency units does cause some smoothing of TFP-growth over time. The productivity growth slowdown of the 1970s – known from studies that do not take into account the age structure of capital – is reduced on the basis of these new capital stock data. The reason is that capital became older over this period. The relationship between the aging of capital and the sign of the vintage effect has

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[13] We have decided to use 1967 as the demarcation of the beginning of the slowdown period instead of the more standard 1973 because of peculiarities associated with the year 1973 (such as the beginning of the oil crisis in the U.S. and the end of Bretton Woods). In Table 5, ‘1967 slowdown’ and also ‘1987 recovery’ should be understood as representing differences between the two surrounding 10-year period in each case rather than single-year events.

a theoretical foundation. While our vintage correction of TFP-growth over the slowdown has the right sign, the magnitude is small.

Based on our new method, we find that the vintage effect accounted for 0.06 percentage points of the 1.34 percentage points decline in overall TFP-growth between the 1957–1967 and the 1967–1977 periods or about 5% of the productivity slowdown. This is about the same order of magnitude as Kendrick (1980) and Clark (1979), though much lower than Wolff (1996). The difference in the findings here from those of Wolff (1996) appears to stem from methodological differences in the two techniques. Wolff (1996) used regression analysis to estimate *indirectly* the contribution of the vintage effect to productivity growth on the basis of the Nelson (1964) formulation. Using a sample of six OECD countries over the period 1950–1989, TFP-growth was regressed on the relative TFP at the beginning of the period, the growth in the capital stock, and the change in the average age of capital in each country. Here, we *directly* estimate the vintage effect for each asset type. Though Wolff (1996) did control for other factors, such as the change in human capital within each country, it is likely that the very strong vintage effect that he estimated is due to the omission of other pertinent variables that explain technological change.

For the manufacturing sector, the vintage effect explained 40% of the (very modest) 0.15 percentage points productivity slowdown in non-durable manufacturing and 27% of the 0.33 percentage points slowdown in durable manufacturing between the 1957–1967 and the 1967–1977 periods. This result is larger than that estimated by Hulten (1992). However, whereas Hulten estimated that the vintage effect accounted for about 20% of the total quality-adjusted technical change in manufacturing over the years 1949–1983, we estimate that it accounted for only about 5% over the 1947–1997 period.

Perhaps, our most significant results are for the 1950s (the 1947–1957 period), when investment in the economy accelerated and the vintage-adjusted capital growth rate well exceeded the BEA growth rate (3.51 and 3.13%, respectively).[14] As a result vintage-adjusted TFP-growth is 8.4% lower than unadjusted TFP-growth for the whole economy (with the figures for the construction sector and the finance, insurance and real estate sector 7 and 34% lower).

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[14] We are grateful to Bob Margo for this observation.

Appendix A

Table A.1
Listing of detailed industries for BEA capital stock data

1	Farms
2	Agricultural services, forestry, and fishing
3	Metal mining
4	Coal mining
5	Oil and gas extraction
6	Non-metallic minerals, except fuels
7	Construction
8	Lumber and wood products
9	Furniture and fixtures
10	Stone, clay, and glass products
11	Primary metal industries
12	Fabricated metal products
13	Industrial machinery and equipment
14	Electronic and other electric equipment
15	Motor vehicles and equipment
16	Other transportation equipment
17	Instruments and related products
18	Miscellaneous manufacturing industries
19	Food and kindred products
20	Tobacco products
21	Textile mill products
22	Apparel and other textile products
23	Paper and allied products
24	Printing and publishing
25	Chemicals and allied products
26	Petroleum and coal products
27	Rubber and miscellaneous plastics products
28	Leather and leather products
29	Railroad transportation
30	Local and interurban passenger transit
31	Trucking and warehousing
32	Water transportation
33	Transportation by air
34	Pipelines, except natural gas
35	Transportation services
36	Telephone and telegraph
37	Radio and television
38	Electric services
39	Gas services
40	Sanitary services
41	Wholesale trade
42	Retail trade
43	Federal reserve banks
44	Other depository institutions
45	Non-depository institutions
46	Security and commodity brokers
47	Insurance carriers
48	Insurance agents, brokers, and service

Table A.1 (*Continued*)

49	Real estate
50	Non-financial holding and investment offices
51	Financial holding and investment offices
52	Hotels and other lodging places
53	Personal services
54	Business services
55	Auto repair, services, and parking
56	Miscellaneous repair services
57	Motion pictures
58	Amusement and recreation services
59	Health services
60	Legal services
61	Educational services
62	Other services, n.e.c.

Appendix B. Discrete time analysis of capital aging

Proposition 1 links the aging of capital to the investment/stock ratio. Erwin Diewert provided the following discrete time proof.

Eq. (5) reads

$$K^s(t) = I(t) + (1 - s - \sigma)I(t-1) + (1 - s - \sigma)^2 I(t-2) + \cdots \tag{10}$$

Defining the number of years embodied in this stock by

$$N^s(t) = 1 \cdot I(t) + 2(1 - s - \sigma)I(t-1) + 3(1 - s - \sigma)^2 I(t-2) + \cdots \tag{11}$$

Eq. (8) reads

$$\bar{A}^s(t) = \frac{N^s(t)}{K^s(t)} \tag{12}$$

Substituting $N^s(t) = K^s(t) + (1 - s - \sigma)\, N^s(t-1)$, a consequence of (11), (12) reads $\bar{A}^s(t) = 1 + (1 - s - \sigma)N^s(t-1)/K^s(t) = 1 + (1 - s - \sigma)\bar{A}^s(t-1)K^s(t-1)/K^s(t)$. Now substituting $K^s(t) = (1 - s - \sigma)\ K^s(t-1) + I(t)$, which follows from (10), just like (6) from (5): $\bar{A}^s(t) = 1 + \bar{A}^s(t-1)[K^s(t) - I(t)]/K^s(t) = 1$ or $\bar{A}^s(t) - \bar{A}^s(t-1) = 1 - [I(t)/K^s(t)]\bar{A}^s(t-1)$. This is Proposition 1 in discrete time.

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