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In the Neoclassical growth theory capital is assumed homogeneous and technical progress disembodied, meaning that all capital units equally benefit from any technological improvement. The disembodied nature of technical progress looks barely unrealistic, as acknowledged by Solow (1960, p 91): "*...This conflicts with the casual observation that many if not most innovations need to be embodied in new kinds of durable equipment before they can be made effective. Improvements in technology affect output only to the extent that they are carried into practice either by net capital formation or by the replacement of old-fashioned equipment by the latest models...*" Accounting for the age distribution of capital is a way to cope with this criticism, and this actually suggested an important stream of the growth literature of the 50's and 60's, giving birth to the vintage capital theory.

An economy is said to have a *vintage capital* structure if machines and equipment belonging to separate generations have different productivity –or face different depreciation schedules as in Benhabib and Rustichini (1991). Let us denote by $I(v)$ the number of machines of vintage v. With zero physical depreciation, vintage technology v is

$$Y(v,t) = F\left(I(v), L(v,t), e^{\gamma v}\right),$$

where $L(v,t)$ is the amount of labor assigned to this vintage at time $t \geq v$. Parameter $\gamma > 0$ designates the rate of technical progress, which is said to be *embodied* since it only benefits vintage v. $F(.)$ has the properties of a neoclassical production function. Vintages produce the same final good

$$Y(t) = \int_{t-T(t)}^{t} Y(v,t)\, dv,$$

where $Y(t)$ is total production and $T(t)$ is the lifetime of the oldest operative vintage.

THE LIFETIME OF CAPITAL. In Johansen (1950), technical progress is labor-saving and technology putty-clay, meaning that capital-labor substitution is permitted *ex-ante*, but not once capital is installed. Because factor proportions are fixed *ex-post*,

$$Y(v,t) = F\left(I(v), e^{\gamma v} L(v,t)\right) = g\left(\lambda(v)\right)\, I(v),$$

where the labor-capital ratio $\lambda(v)$ and the size of the capital stock $I(v)$ are both decided at the time of installation, and employment is $L(v,t) = \lambda(v)e^{\gamma v}I(v)$.

In Johansen, *obsolescence* determines the range of active vintages. Quasi-rents of vintage v at date t are proportional to $g(\lambda(v)) - \lambda(v)\ e^{\gamma v}\ w(t)$, where $w(t)$ is the equilibrium wage. Since wages are permanently growing, as a direct consequence of technical progress, quasi-rents are decreasing. Machines of vintage v are operated as long as their quasi-rents remain positive. Consequently, the scrapping age is defined by $T = t^* - v$ where $g(\lambda(v)) = \lambda(v)\ e^{\gamma v} w(t^*)$. Therefore, Johansen's framework leads to an endogenous, finite lifetime of capital.

THE EMBODIED QUESTION. In Solow (1960), vintage technology is Cobb-Douglas

$$Y(v,t) = \left[\mathrm{e}^{\gamma v} I(v)\right]^{1-\alpha}\ L(v,t)^{\alpha},$$

and the capital-labor ratio adjusts continuously. The embodiment hypothesis takes the form of quality adjustments, with capital's quality growing at rate γ. In sharp contrast to Johansen, capital lifetime needs not be finite, since under Cobb-Douglas technology any wage cost could be covered by assigning arbitrary small amounts of labor.

A striking outcome of Solow's model is its aggregation properties. Denote by $L(t)$ the total labor supply, and define quality adjusted capital as

$$K(t) = \int_{-\infty}^{t} \mathrm{e}^{\gamma v} I(v)\ \mathrm{d}v. \tag{1}$$

Since marginal labor productivity equalizes across vintages, aggregate output becomes

$$Y(t) = K(t)^{1-\alpha} L(t)^{\alpha}.$$

Aggregate vintage technology in Solow (1960) degenerates into a neoclassical production function. However, by differentiating (1), the motion law for capital is slightly different

$$K'(t) = \ \mathrm{e}^{\gamma t}\ I(t)$$

reflecting embodied technical change. Since $\mathrm{e}^{-\gamma t}$ measures the relative price of investment goods at equilibrium, the value of capital is by definition $A(t) = e^{-\gamma t}\ K(t)$, and evolves following

$$A'(t) = I(t) - \gamma\ A(t).$$

Technological progress operates as a steady improvement in equipment quality, which in turn implies obsolescence of the previously installed capital. In Solow, obsolescence does not show up through finite time scrapping but through labor reallocation reflecting a declining value of capital.

This important point has been at the heart of a recent literature on the *productivity slowdown* and the *information technology revolution* (see Whelan, 2002). Actually, the potential implications for growth of embodied technical progress was tremendously controversial in the 60s. In a famous statement, Denison (1964) claimed "the embodied question is unimportant." His argument was merely quantitative and restricted embodiment to changes in the average age of capital in a one-sector growth accounting exercise. In particular, his reasoning omits *de facto* the relative price of capital channel. Greenwood, Hercowitz and Krusell (1997), by using Gordon (1990)'s estimates of the relative price of equipment, quantitatively evaluate the Solow model, claiming that around 60% of US per-capita growth is due to embodied technical change. As pointed out by Hercowitz (1998), Gordon's series have been good news for the Solowian view.

Replacement Echoes. Solow *et al.* (1966) examine the polar case, where factor substitution is not allowed neither *ex-ante* nor *ex-post*. Under Leontief technology, $Y(v,t) = Y(v) = I(v) = e^{\gamma v}\ L(v)$, for all $t \geq v$. One unit of vintage capital v produces one unit of output once combined with $e^{-\gamma v}$ units of labor. Technical progress is embodied and takes the form of a decreasing labor requirement. For the same reasons as in Johansen, capital goods are scrapped at finite time.

Under constant saving rate, and some technical assumptions, Solow *et al.* show convergence to a unique balanced growth path, delivering the same qualitative asymptotic behavior as the neoclassical growth model. This was quite disappointing, since under finite lifetime one would have expected investment burst from time to time, giving rise to the so-called *replacement echoes*.

Let normalize the labor supply to unity. From labor market clearing, $\int_{t-T(t)}^{t}\ L(v)\ dv = 1$. Under constant lifetime, time differentiation of the equilibrium condition yields $L(t) = L\left(t-T\right)$, implying that investment is mainly driven by replacement activities. When obsolete capital is destroyed, new investments are needed to replace the scrapped machines, creating enough jobs to clear the labor market. As a direct consequence, job creation and investment have a periodic behavior, implying that investment cycles are reproduced again and again in the future.

Solow *et al* did not find echoes because of the constant saving rate assumption, which completely decouples investment from replacement. In an optimal growth model with linear utility and the same technological assumptions, Boucekkine, Germain and Licandro (1997) show (finite time) convergence to a constant lifetime, letting replacement echoes operate and generate everlasting fluctuations in investment, output and consumption. Under strictly concave preferences, fluctuations do arise in the short-run but get dampened in the long-run by consumption smoothing (see Boucekkine *et al.*, 1998). Therefore, the short-run dynamics of vintage capital models strikingly differ from the neoclassical growth model, provided capital and labor are to some extent complementary, consistently with the observed dynamics of investment both at the plant level (Doms and Dunne, 1998) and the aggregate level (Cooper, Haltiwanger and Power, 1999). Non-monotonic behavior has also been shown by Benhabib and Rustichini for vintage models with non-geometric depreciation.

Vintage human capital. The vintage capital growth literature typically considers labor as a homogenous good. However, like physical capital is heterogenous, so is the labor force. The concept of vintage human capital has been explicitly used in the 90s to treat some specific issues related to technology diffusion, inequality and economic demography.

TECHNOLOGY DIFFUSION. In Chari and Hopenhayn (1991) and Parente (1994), individuals face the dilemma of whether to stick to an established technology or to adopt a new and better one. The trade-off is the following: adopting allows the use of an advanced technology at the cost of loosing expertise, the specific human capital accumulated on the currently used technique. Chari and Hopenhayn model it in a two-period overlapping generations model where different vintage technologies, operated by skilled and unskilled workers, coexist. Old workers are experts in the specific vintage technology they have run when young. The degree of complementary between skilled and unskilled labor affects negatively the velocity of technological diffusion, since young individual have large incentives in investing in old technologies when their unskilled labor endowment is highly complementary to the skilled labor of the old.

INEQUALITY. Jovanovic (1998) argues that vintage capital models are particularly well suited to explain income disparities across individuals and across countries. As in Johansen, different vintages coexist even though new machines are more productive. Under the assumption that machines' quality and labor's skill are complementary, the best machines are operated by the best skilled individuals, exacerbating inequality. Human capital accumulation drives growth by promoting the investment in new vintage capital technologies. The best skilled workers are immediately assigned to the frontier technology, the second bests go to the machines just below the frontier, and so on. Even if it goes at odds with Chari and Hopenhayn, where adoption costs induce a much slower switching of technologies, frictionless reassignment has the virtue, consistent with cross country evidence, of implying persistent inequality in contrast to Parente (1994) which bears leapfrogging.

DEMOGRAPHICS. One likely channel through which demographics affect growth is the size, quality and composition of the work force. In this perspective, generations of workers can be understood as being vintages of human capital. In a continuous time overlapping generations framework, Boucekkine, de la Croix and Licandro (2002) model the vintage specificity of human capital from schooling decisions. Individuals optimally decide how many years to spend at school as well as their retirement age; life expectancy has a positive effect on both, because of its beneficial impact on the return of education. In such a framework, the vintage specificity of human capital does not depend on technological vintages as in Chari and Hopenhayn (1991) but on cohort specific demographic characteristics, including education.

The observed relation between demographic variables, such as mortality, fertility and cohort sizes, and growth is anything but linear. Since a key element is between-generation differences in human capital, these nonlinearities may be modeled by the mean of a vintage structure of population. Boucekkine et al. generate nonlinear relationships between economic growth and both population growth and life expectancy. A longer life, for example, has several conflicting effects. On one hand, it raises the incentives to educate and reduces the depreciation rate of aggregate human capital. But on the other, an older population, who did their schooling a long time ago, is harmful for economic growth.

References

Benhabib J. and A. Rustichini (1991), "Vintage Capital, Investment, and Growth." *Journal of Economic Theory* 55, 323–339.

Boucekkine R., D. de la Croix and O. Licandro (2002), "Vintage human capital, demographic trends and growth." *Journal of Economic Theory* 104, 340–375.

Boucekkine R., M. Germain and O. Licandro (1997) "Replacement echoes in the vintage capital growth model." *Journal of Economic Theory* 74, 333–348.

Boucekkine R., M. Germain, O. Licandro and A. Magnus (1998), "Creative destruction, investment volatility and the average age of capital." *Journal of Economic Growth* 3, 361–384.

Chari V.V. and H. Hopenhayn (1991), "Vintage human capital, growth, and the diffusion of new technology." *Journal of Political Economy* 99, 1142–1165.

Cooper R., J. Haltiwanger and L. Power (1999), "Machine replacement and the business cycle: Lumps and bumps." *American Economic Review* 84, 921–946.

Denison E. (1964), "The unimportance of the embodied question." *American Economic Review - Papers and Proceedings* 54, 90–94.

Doms M. and T. Dunne (1998), "Capital adjustment patterns in manufacturing plants." *Review of Economic Dynamics* 1: 409–429.

Gordon R. (1990), *The measurement of durable goods prices.* University of Chicago Press.

Greenwood J., Z. Hercowitz and P. Krusell (1997), "Long-run implications of investment specific technological change." *American Economic Review* 87, 342–362.

Hercowitz Z. (1998), "The embodiment controversy: A review essay." *Journal of Monetary Economics* 41, 217–224.

Johansen L. (1950), "Substitution Versus fixed production coefficients in the theory of economic growth." *Econometrica* 29, 157–176.

Jovanovic B. (1998), "Vintage capital and inequality." *Review of Economic Dynamics* 1, 497–530.

Parente S. (1994), "Technology adoption, learning-by-doing, and economic growth." *Journal of Economic Theory* 63, 346–369.

Solow R. (1960), "Investment and technological progress." In K. Arrow, S. Karlin and P. Suppes (eds.), *Mathematical Methods in Social Sciences 1959*, 89–104. Stanford University Press.

Solow R., J. Tobin, C. Von Weizsacker and M. Yaari (1966), "Neoclassical growth with fixed factor proportions." *Review of Economic Studies* 33, 79–115.

Whelan, K. (2002), "Computers, obsolescence and productivity." *The Review of Economics and Statistics* 84, 445–461.