Vintage Capital

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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 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 $Y(v,t)$ is the output of vintage v at time $t \geq v$ and $L(v,t)$ is the amount of labor assigned to this vintage. 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.

Beside realism, vintage capital models were initially thought to be able to generate quite different long run properties and short term dynamics from neoclassical growth models. Because the productivity gap between new and old vintages is increasing over time, the latter need not be operated forever, and contrary to the neoclassical growth theory, the lifetime of capital goods might well be finite (Johansen, 1959). Such a property was thought to involve non-monotonic transition dynamics governed by the replacement of scrapped goods, known as the replacement echoes principle, which again sharply departs from neoclassical growth models. On a more general ground, vintage capital models were at the heart of the embodiment controversy, which opposed Solow to some leading growth theorists and empiricists, among them Phelps (1962) and Denison (1964). While the former argued that accounting for the fraction of technological progress which is exclusively conveyed by capital accumulation (namely embodied technical progress) is important to account for growth, Phelps argued that the decomposition of technical progress is irrelevant in the long run. Recent studies notably by Gordon (1990) have resuscitated this controversy as we shall see later. Before developing all these themes, it should be noted that whereas the early vintage capital theory was primarily focusing on physical capital accumulation, recent contributions have taken the same view of human capital accumulation (see Chari and Hopenhayn, 1991). Vintage human capital is either generated by successive vintages of technologies which induce specific skills or by demographic conditions. Such contributions have brought out a new and quite appealing understanding of the mechanisms behind technology diffusion and demographic transitions for example. We shall also review them briefly.

THE LIFETIME OF CAPITAL. In Johansen (1959), technology is putty-clay meaning that capital-labor substitution is permitted *ex-ante*, but not once capital is installed. Technological progress is assumed labor-saving. 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 $L(v,t) = \lambda(v) e^{\gamma v} I\left(v\right)$.

In Johansen, *obsolescence* determines the range of active vintages. Quasi-rents of vintage v at date t are proportional to $g\left(\lambda(v)\right) - \lambda(v)\ e^{\gamma v}\ w(t)$, 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.

Replacement Echoes. If capital lifetime is finite, there might be a room for replacement echoes as mentioned above. Solow *et al.* (1966) examine this question in the simpler case of a Leontief technology, when factor substitution is not allowed neither *ex-ante* nor *ex-post*. In such a case, $Y(v,t) = Y(v) = I(v) = e^{\gamma v}\ L(v)$, 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 in finite time. Using in addition a 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 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 $L(t) = L(t-T)$, 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.

THE EMBODIMENT HYPOTHESIS. A crucial property of vintage capital models is the embodied nature of technological progress: the incorporation of innovations into the production process cannot be achieved without the acquisition of the new vintages which are their exclusive material support. According to Solow (1960), embodiment can have crucial implications for growth accounting. To make the point, he considers a Cobb-Douglas vintage technology

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

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.

Vintage human capital. The vintage capital growth literature typically considers labor as a homogenous good. However, just as 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.

In a world with a continuous pace of innovations, a representative individual faces the typical question of whether to stick to an established technology or to move to a new and better one. The trade-off is the following: switching to the new technique would allow him to employ a more advanced technology but he would lose the expertise, the *specific human capital*, accumulated on the old technique. In Chari and Hopenhayn (1991) and Parente (1994), individuals face exactly this dilemma. In such frameworks the generated vintage human capital distributions essentially mimic the vintage distribution of technologies, the time sequence of innovations being generally exogenously given. Chari and Hopenhayn consider 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.

Jovanovic (1998) argues that vintage capital models are particularly well suited to explain income disparities across individuals and across countries. The main mechanism behind them is the following. Under the assumption that machines' quality and labor's skill are complementary, the best machines are assignment by the best skilled individuals, exacerbating inequality. If reassignment is frictionless, then the best skilled workers are immediately assigned to the frontier technology, the second best go to the machines just below the frontier, and so on. Even though it is 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.

On the theoretical ground, Jovanovic's contribution is an important contribution to the vintage capital literature to the extent that it addresses the hard problem of combining vintage physical capital and vintage human capital in a framework where the vintage distributions of both assets are endogenous. Jovanovic uses an assignment model *à la* Sattinger (1975) to solve this difficult problem. Firms combine machines and workers in fixed proportions, say one machine for one worker, at every instant. Because labor resources are fixed, the latter fixed proportions assumption implies that old machines become unprofitable at a finite time as in Johansen. Vintage human capital comes from human capital accumulation à la Lucas (1988) : the growth of the stock of human capital determines the maximal quality of human capital available: if the worker has human capital, h, and works a fraction of time u (in production), then her skill is given by $s = u\ h$. The typical assignment problem of a firm having acquired capital of a given vintage is to find the optimal vintage human capital or skill of the associated worker (via profit maximization), which allows to achieve the pairing of skills and machines at the basis of the persistent inequality mechanism outlined above.

Demographics. One likely channel through which demographics affect growth is the size, quality and composition of the work force. From 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.

Conclusion. After a relatively long stagnation, the vintage capital literature, which was a fundamental growth area in the 60s, has been experiencing a revival since the early 90s. This revival is due to several factors, among them: the rising support to the Solowian view of investment following Gordon's fundamental work on the price of durable goods, the emergence of a new vintage capital growth theory led by Benhabib and Rustichini relying on a novel and appropriate mathematical set-up, notably the increasingly common view that some fundamental economic growth issues (like technology diffusion for example) do require the vintage structure to be better appraised. Of course, many tasks within this new literature remain to be addressed. In particular, much work is needed to bring the vintage models closer to the data. The work of Gilchrist and Williams (2000) is fundamental is this respect.

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