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Technological-Knowledge Dynamics in Lab-Equipment Models of Quality Ladders

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The Perpetual Inventory Model (PIM) assumes that, in each period, an arbitrary constant fraction of technological-knowledge stock is lost. By connecting the aggregate resource constraint with firms' market value, we give a theoretical background to the PIM by showing that the technological-knowledge accumulation follows a dynamic process with an endogenous depreciation rate, which remains stable in steady state. Moreover, we relate different concepts of technological-knowledge used in the literature.

Keywords: endogenous growth, endogenous depreciation rate, Perpetual Inventory Model, technological-knowledge dynamics

JEL Classification: O30, O41

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1 Introduction

Empirical estimates of the stock of ideas or technological knowledge usually build on the Perpetual Inventory Model (PIM), according to which the stock value suffers geometric depreciation at an arbitrated constant "obsolescence" rate (e.g., Coe and Helpman, 1995; Frantzen, 1998; and Park, 2004). This approach is not free of criticism, as "a constant depreciation rate implies that depreciation takes place in a mechanical way", independently of whether R&D is carried out or not (Bitzer and Stephan, 2007, p. 181). Similarly to the process of physical capital accumulation, this mechanism implies that a constant fraction of the technological-knowledge stock is lost with the passage of time and thus, if all R&D stops, that stock converges in the long run to zero.

Bitzer and Stephan (2007) study an econometric model that takes into account the Schumpeterian link between present R&D and the depreciation of past R&D capital stock, in order to estimate the technological-knowledge stock. The authors build a stock-flow equation according to which every R&D investment first induces an increase in the R&D capital stock, but thereafter renders the existing stock obsolete. The depreciation rate depends on past R&D investments and is therefore not constant as in the PIM. This dependency yields the desirable result that the R&D capital stock converges to a positive constant if R&D ceases.

In this paper, we argue that the dynamics of the technological-knowledge stock can be represented by a mechanism similar to the one used for physical-capital accumulation, as long as we take into account the endogeneity of the depreciation (obsolescence) rate and take a long-run (steady-state) view of the process of technological-knowledge accumulation. This approach is in line with the notion of "endogenous obsolescence" explored by Caballero and Jaffe (1993), while it gives theoretical background to the assumption of geometric depreciation at a constant rate in the PIM. Also, we make explicit the link between our concept of technological knowledge and the measure of knowledge stock proposed by Griliches (1979).

Our contribution is defined within a lab-equipment framework (Rivera-Batiz and Romer, 1991) nested in an endogenous growth model of quality ladders in the intermediate-good sector (e.g., Aghion and Howitt, 1998, ch. 3, and Barro and Sala-i-Martin, 2004, ch. 7). As in the standard model, the final-good production function is Cobb-Douglas, each quality-adjusted intermediate good is produced by a single-product firm with a constant-return technology, only (potential) entrants do R&D and innovation arrival follows a Poisson process. The dynamic equation for the technological-knowledge stock is obtained through the explicit derivation of the aggregate resource constraint from households' balance sheet and flow budget constraint. This contrasts with the standard procedure in quality-ladders literature, which assumes directly the aggregate resource constraint.

Similarly to the standard growth model with physical capital accumulation, the stock of technological knowledge increases with the flow of gross investment (vertical R&D) and decreases due to depreciation (obsolescence) over time. Contrary to physical-capital accumulation models, the depreciation rate is endogenous (it is the Poisson arrival rate of vertical innovation), since it depends on R&D activity itself, thus reflecting the Schumpeterian process of creative destruction. Moreover, the depreciation rate is constant in steady state. Hence, according to our model-based approach, one should not view the assumption of a constant depreciation rate as "a serious drawback of the PIM" (Bitzer and Stephan, 2007, p. 181), as it conforms with the theoretical prediction of a wide class of endogenous growth models of vertical innovation. Also, the endogeneity of the depreciation rate in the growth models of quality ladders allows for its explicit computation through proper calibration of the model, after the determination of its steady-state equilibrium, in contrast to the arbitrary choice of values in the standard PIM applications.

The paper is organised as follows. Section 2 briefly sketches the standard model of quality ladders in a lab-equipment framework. In section 3, the aggregate resource constraint and the accumulation equation for the firms' total market value are derived. In section 4, the technological-knowledge dynamics is made explicit. Section 5 concludes.

2 The quality-ladders model

We follow the standard multi-sector model of quality ladders (Aghion and Howitt, 1998, ch. 3; Barro and Sala-i-Martin, 2004, ch. 7). This is a dynamic general equilibrium model of a closed economy where there is a single competitively-produced final good, Y, that can be used in consumption, C, production of intermediate goods, X, and vertical R&D activities, R. Final output is the numeraire (that is, we set its price equal to unity). Labour, L, is inelastically supplied by households to final-good firms and, by assumption, does not vary over time. In turn, families invest in firms' equity.

2.1 Production

The final-good production function is

$$Y(t) = L(t)^{1-\alpha} \int_0^N \lambda(\omega, t) x(\omega, t)^\alpha d\omega \tag{1}$$

where $L(t)$ is labour input; $(1-\alpha)$, $0 < \alpha < 1$, is the labour share in production; $x(\omega, t)$ is the amount used of the latest generation of the intermediate good ω, weighted by its quality level $\lambda(\omega, t)$, and $N > 0$ is the measure of how many different intermediate goods ω exist, which we assume to be constant.

Each firm in the final-good sector seeks to maximise profit, taking the price of ω relative to the final-good price, $p(\omega, t)$, and the labour wage, $w(t)$, also relative to the final-good price, as given. The intermediate good is nondurable and entails a unit marginal cost of production, measured in terms of Y. Since there is a continuum of intermediate goods, one can assume that firms are atomistic and take as given the price of final output (numeraire); monopolistic competition, therefore, prevails and firms face isoelastic demand curves. The optimal intermediate good price is the usual monopoly price markup, $p(\omega, t) \equiv p = \frac{1}{\alpha}$, constant over time and across industries. The quantity produced of intermediate good ω is $x(\omega, t) = L\left[\lambda(\omega, t)\alpha^2\right]^{\frac{1}{1-\alpha}}$ and the profit accrued by the monopolist in ω is $\pi(\omega, t) = L \cdot \left(\frac{1-\alpha}{\alpha}\right) \alpha^{\frac{2}{1-\alpha}} \lambda(\omega, t)^{\frac{1}{1-\alpha}}$. Substituting in (1) and aggregating across the economy yields $Y(t) = L \cdot \left(\alpha^2\right)^{\frac{\alpha}{1-\alpha}} \int_0^N \lambda(\omega, t)^{\frac{1}{1-\alpha}} d\omega$, $X(t) = \int_0^N x(\omega, t) d\omega = L \cdot \left(\alpha^2\right)^{\frac{1}{1-\alpha}} \int_0^N \lambda(\omega, t)^{\frac{1}{1-\alpha}} d\omega$, and $\Pi(t) = \int_0^N \pi(\omega, t) d\omega = L \cdot \left(\frac{1-\alpha}{\alpha}\right) \alpha^{\frac{2}{1-\alpha}} \int_0^N \lambda(\omega, t)^{\frac{1}{1-\alpha}} d\omega$.

Having in mind that, in equilibrium, labour wage, w, and intermediate-good price, p, are equated to the marginal product of labour and the marginal product of intermediate goods, respectively, the following aggregate relations are derived: $wL = (1-\alpha)Y$; $X = \alpha^2 Y$, $pX = \alpha Y$ and $\Pi = X \cdot (p-1) = \alpha Y - \alpha^2 Y$.

Now, let $q(\omega, t) \equiv \lambda(\omega, t)^{\frac{1}{1-\alpha}}$ and define the representative intermediate good as the average of all intermediate goods, such that its quality is $\bar{q} \equiv E_\omega(q)$, the average of q over industries, i.e., $\int_0^N q(\omega,t)d\omega = \bar{q}(t)N$. Hence, $X(t) = x(\bar{q})N$ and $\Pi(t) = \pi(\bar{q})N$.

2.2 Vertical R&D

Firms decide over their optimal vertical-R&D level, which constitutes the search for new designs that lead to a higher quality of existing intermediate goods. Each new design is granted a patent, meaning that a successful researcher retains exclusive rights over the use of his/her improved intermediate good. Only (potential) entrants can do R&D and innovation arrival follows a Poisson process, with instantaneous probability of R&D success, I.[1] With free-entry into each vertical R&D race and perfect competition among entrants, the R&D expenditures of individual entrants will be negligible. Thus, we have the free-entry condition

$$I(\omega,t) \cdot V(\omega,t) = R(\omega,t) \tag{2}$$

where V is the *expected* discounted value of profits associated to the next innovation, $V(\omega,t) = \int_t^\infty \pi(\omega,t)e^{-\int_t^s (r(v)+I(\omega,v))dv}ds$, where r is the equilibrium market real interest rate. This equation reflects the fact that, if a profit flow can stop when a Poisson event with arrival rate I occurs, then we can calculate the *expected* present value of the stream of profit as if it never stops, but adding I to the discount rate. Thus, we can interpret $r + I$ as an *effective* discount rate. V can be interpreted as the market value of the patent or the value of the monopolist firm owned by households. From (2), we can aggregate across ω to get $R(t) = \int_0^N R(\omega,t)d\omega$.

2.3 Households

Households consume and collect income (dividends) from investments in financial assets (equity) and labour income. They choose the trajectory of final-good aggregate consumption $\{C(t), t \geq 0\}$ to maximise a standard discounted lifetime utility. Intertemporal utility is maximised subject to the flow budget constraint

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[1] The specific way each innovation arrival impacts on intermediate-good quality level λ depends on whether we consider a model with intersectoral spillovers (Aghion and Howitt, 1998, ch. 3) or not (Barro and Sala-i-Martin, 2004, ch. 7). In any case, we take the usual assumption that each entrant possesses the same R&D technology, specified such that I is constant across industries at every t, i.e., $I(\omega,t) = I(t)$, and also constant over time in balanced-growth path.

$$\dot{a}(t) = r(t)a(t) + w(t)L - C(t) \tag{3}$$

where a stands for households' financial assets (equity) holdings, measured in terms of final-good output Y. The maximisation of discounted lifetime utility is also subject to the initial level of wealth, and to the usual no-Ponzi-schemes and transversality conditions. Households take the real labour wage, w, and the real rate of return on financial assets, r, as given. The latter equals dividend payments in units of asset price corrected by the Poisson death rate

$$r(t) = \frac{\pi(t)}{V(t)} - I(t) \tag{4}$$

This equation can be read as an arbitrage condition for investors, which requires that the real interest rate equals the dividend rate, $\frac{\pi}{V}$, plus the rate of capital gain, $-I$.

3 Aggregate resource constraint and firms' market-value dynamics

Consider the representative intermediate good, with quality $\bar{q}$. The balance sheet of households equates the value of equity holdings to the market value of firms, that is

$$a(t) = V(\bar{q})N \tag{5}$$

Hence, we can characterise the change in the value of equity as

$$\dot{a}(t) = \dot{V}(\bar{q})N \tag{6}$$

By substituting (3) in the left-hand side of (6) and letting $K \equiv VN$, we get

$$\dot{K}(t) = r(t)K(t) + w(t)L - C(t) = [r(t) + I(t)]\,K(t) + w(t)L - C(t) - I(t)K(t) \tag{7}$$

Also, from (4) and (5), we observe that

$$r(t) + I(t) = \frac{\pi(\bar{q})}{V(\bar{q})} \Leftrightarrow [r(t) + I(t)]\, a(t) = \pi(\bar{q})N \tag{8}$$

The equation above implies that $\Pi = \pi N = (r + I)K$ for the representative intermediate good. Using the latter, together with $wL = (1 - \alpha)Y$ and $\Pi = \alpha Y - \alpha^2 Y$ in (7), and simplifying with $X = \alpha^2 Y$, yields

$$\dot{K}(t) = Y(t) - X(t) - C(t) - I(t)K(t) \tag{9}$$

which is the accumulation equation for K, i.e., firms' total market value. If we solve (9) in order to Y, we have the aggregate resource constraint

$$Y(t) = X(t) + C(t) + R(t) \tag{10}$$

where

$$R(t) = \dot{K}(t) + I(t)K(t) \Leftrightarrow \dot{K}(t) = R(t) - I(t)K(t) \tag{11}$$

Equation (10) tells us that total final-good output, Y, is allocated among consumption, C, production of intermediate goods, X, and vertical R&D expenditures, R, thus being a *product market equilibrium* equation.

As for (11), the first term on the right-hand side, R, represents the *gross investment* in technological knowledge through vertical R&D at time t, whereas the second term, IK, represents the *depreciation* of the total market value of firms (i.e., lived patents) due to the impact (obsolescence) of the stochastic arrival of vertical innovations on the existing technological-knowledge stock, i.e., the Schumpeterian effect of creative destruction. This means that $R = 0 \Rightarrow I = 0$ and, thus, $\dot{K} = 0$. Equation (11) has obvious similarities to the accumulation equation of physical capital in the standard Ramsey model. However, the depreciation rate displayed by our model is not exogenous, but rather an endogenous function of vertical R&D activity, in line with the notion of "endogenous obsolescence" explored by Caballero and Jaffe (1993).

According to our assumptions, in a steady-state equilibrium with $R > 0$, the Poisson rate $I > 0$ is constant, meaning that (11) can be re-written as

$$\dot{K}(t) = R(t) - IK(t) \tag{12}$$

The latter is identical to the dynamic equation postulated under the PIM, and where technological-knowledge stock is measured as "R&D capital stock" (e.g., Coe and Helpman, 1995).[2] Within our general-equilibrium setting, the "R&D capital stock" equals firms' total market value, K, and thus households' total financial assets, a.

Hence, according to our model-based approach, one should not view the assumption of a constant depreciation rate as "a serious drawback of the PIM" (Bitzer and Stephan, 2007, p. 181), as it conforms with the theoretical prediction of a wide class of endogenous growth models of vertical innovation. The constancy of the depreciation rate in steady state implies that the view of a constant fraction of technological-knowledge stock being lost with the passage of time is a good approximation in the long run, whereas the endogeneity of the depreciation rate ensures that, if all R&D stops, that stock does not converge to zero in the long run.[3]

Our operationalisation of the concept of technological-knowledge stock can be linked to the measure of knowledge stock proposed by Griliches (1979) and analysed recently by Klette and Kortum (2004). For Griliches, the "technical knowledge" stock is some lag function of *past* R&D. Klette and Kortum (2004) propose a measure of knowledge stock conditional on past R&D expenditures, R, considering that the appropriate discount rate on past R&D is the intensity of creative destruction. In our model, this is the Poisson arrival rate I. Hence, if we let K denote the R&D capital stock and take I as time-variable, we can write

$$K(t) = \int_{t_0}^{t} e^{-\int_s^t I(\tau)d\tau} R(s)ds \qquad (13)$$

where t_0 is the time on which the first intermediate-good line was born.[4] If we time-differentiate (13), we get $\dot{K}(t) = R(t) - I(t)K(t)$, which is (11).

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[2] An alternative approach is to apply PIM to patent-count data in order to compute the "stock of ideas" (see, e.g., Porter and Stern, 2000, who, however, do not consider obsolescence, and Pessoa, 2005).

[3] In fact, the model used by Bitzer and Stephan (2007) yields a constant depreciation rate when (lagged) R&D investment grows at the same rate as technological-knowledge stock, which is exactly what happens in steady-state equilibrium in the quality-ladders models.

[4] For an alternative measure of knowledge stock, set within a model that takes into account obsolescence and diffusion effects, see Caballero and Jaffe (1993).

4 Technological-knowledge dynamics

In section 3 we studied the dynamics of technological-knowledge stock through the dynamics of firms' total market value, K. In order to perform a direct study of the former, we need a measure of R&D effectiveness. Take the assumption that the instantaneous probability of R&D success is given by a relation exhibiting constant returns in R&D expenditures[5]

$$I(\omega, t) = R(\omega, t)\Phi(\omega, t) \tag{14}$$

where the function Φ, to be defined below, is the same for every ω and captures the effect of the current technological knowledge in ω on R&D effectiveness. By substituting (14) in (2), we get

$$V(\omega, t) = \frac{1}{\Phi(\omega, t)} \tag{15}$$

We must also define a measure of technological-knowledge stock. In a quality-ladders model *without* intersectoral spillovers, such as Barro and Sala-i-Martin (2004, ch. 7), the relevant measure is the *aggregate quality index* $A(t) \equiv \int_0^N \lambda(\omega, t)^{\frac{1}{1-\alpha}} d\omega$, with $\Phi(\omega, t) \equiv \frac{1}{\zeta\lambda(\omega,t)^{\frac{1}{1-\alpha}}}$, where $\zeta > 0$ is a fixed cost of doing R&D. Substitute the latter in (15), to get $V(\bar{q}) = \zeta\bar{q}(t)$, with $\bar{q}(t) = \frac{A(t)}{N}$. From here, we have

$$a(t) = V(\bar{q})N = \zeta A(t) \tag{16}$$

and, thus

$$\dot{A}(t) = \frac{1}{\zeta}R(t) - I(t)A(t) \tag{17}$$

In a quality-ladders model *with* intersectoral spillovers, such as Aghion and Howitt (1998, ch. 3), the relevant measure is the *leading-edge quality index* $\lambda^{max} \equiv max\left[\lambda(\omega)\right]$, for each t, with $\Phi(\omega, t) \equiv \frac{1}{\zeta\lambda^{max}(t)}$. Following the same steps as before, we get

$$a(t) = V(\bar{q})N = \zeta N\lambda^{max}(t) \tag{18}$$

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[5] The assumption of constant returns in R&D activities, instead of decreasing returns as in, e.g., Segerstrom and Zolnierek (1999), simplifies the analysis but does not change the results in any fundamental way.

and, thus

$$\dot{\lambda^{max}}(t) = \frac{1}{\zeta N} R(t) - I(t)\lambda^{max}(t) \tag{19}$$

We find that, whatever the measure of technological-knowledge stock chosen, its dynamics is commanded solely by the dynamics of households' total financial assets, a, while (17)-(19) confirm the role of I as the endogenous depreciation rate of technological knowledge.[6]

In this setting, the depreciation rate can be explicitly computed through proper calibration of the model, after the determination of its steady-state equilibrium. We present a simple illustration, based on the analytical expression for the steady-state value of I derived in Barro and Sala-i-Martin (2004, ch. 7) and the following set of baseline parameter values: $\zeta = 0.8$, $\lambda = 2.5$, $\rho = 0.02$, $\theta = 1.5$, $\alpha = 0.4$, $L = 1$.[7]The obtained Poisson arrival rate is of 3 percent in steady state.[8]This result contrasts with the arbitrary values chosen in the standard PIM applications, typically between 5 and 20 percent (e.g., Coe and Helpman, 1995).

5 Conclusion

Empirical estimates of technological-knowledge stock usually build on the PIM, according to which the stock value suffers geometric depreciation at an arbitrated constant "obsolescence" rate. This approach has been contested recently in the literature, since, similarly to the process of physical-capital accumulation, this mechanism implies that a constant fraction of technological-knowledge stock is lost with the passage of time. Thus, if all R&D stops, that stock converges in the long run to zero.

In this paper, we argue that the dynamics of technological-knowledge stock can

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[6] Notably, it can be shown equations (16)-(18) guarantee that, given $R(t) = \int_0^N R(\omega, t)d\omega$ and (11), the consistency condition $\int_0^N R(\omega, t)d\omega = \dot{K}(t) + I(t)K(t)$ is verified.

[7] The values for λ, θ, ρ and α where set in line with previous work on growth and guided either by empirical findings or by theoretical specification. The values of the remaining parameters were chosen in order to calibrate the steady-state aggregate growth rate around 2.5 percent/year. The normalization of L to unity at every t implies that the results of the model do not depend on the value of the growth rate of that variable (either zero or not), and also that all aggregate magnitudes can be interpreted as per capita magnitudes.

[8] Interestingly, this value corresponds to the average of the estimates provided by Caballero and Jaffe (1993) for the creative-destruction rate in the US.

in fact be represented by a mechanism similar to the one used for physical-capital accumulation, as long as we take into account the endogeneity of the depreciation rate and take a long-run (steady-state) view of the process of technological-knowledge accumulation.

In this setting, we present the explicit computation of the depreciation rate through proper calibration of the model as an alternative route to the arbitrary choice of values in the standard PIM applications. We leave the application of this approach to the data for further research.

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