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Why are wages of both skilled and unskilled workers lower in poor countries?

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Abstract

We introduce credit constraints into a standard model of endogenous growth. In the presence of credit constraints, firms in poor countries face higher borrowing costs which in turn negatively affects capital accumulation and labor productivity in the final-goods producing sector. Furthermore, lower capital intensity of production makes R&D activity less profitable. As a result, both demand for skilled labor and return to skill are lower in poor countries. Domestic financial frictions may therefore be the key to understanding the persistent wage differentials in favor of rich countries and international migration patterns we observe.

Keywords: Skilled Wages; Migration; Credit Constraints; R&D; Endogenous Growth

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In evaluating different models of growth, I have found that Lucas's (1988) observation, that people with human capital migrate from places where it is scarce to places where it is abundant, is as powerful a piece of evidence as all the cross-country growth regressions combined (Romer, 1994).

1 Introduction

The neoclassical model predicts that the rate of return on both capital and labor is directly related to scarcity. Lucas (1988) emphasized the fact that international pattern of migration and wage differentials are very difficult to reconcile with a neoclassical model. If skilled labor is a scarce factor in poor countries, the return to skill in these countries should be high, and this should encourage the migration of skilled workers out of rich countries.[1] In practice, the opposite is true. Labor migration is overwhelmingly toward the richest countries. Countries in the richest quintile are all net recipients of migrants (Easterly and Levine, 2001).[2]

Embodied in this flow of labor are flows of skilled individuals from poor countries toward rich countries, the famous "brain drain." Human capital is flowing to where it is already abundant - the rich countries. Why is this the case? Wage differential may be part of the story, but this raises the question of what accounts for such differentials. Differences in the quality of life, professional advancement, safety for their families may play a role, as may the desire to work with a broader group of similarly skilled

[1]The facts do not support these predictions. Skilled workers earn less (adjusted for purchasing power), rather than more, in poor countries (Commander et al., 2004). Furthermore, both physical and human capital flow toward rich areas, as does unskilled labor (Easterly and Levine, 2001).

[2]Carrington and Detragiache (1998) found that in 51 of 61 developing countries in their sample, people with a university education were more likely to emigrate to the United States than people with a secondary education.

individuals (Gibson and Mckenzie, 2011). Despite these differences such persistent wage differentials are puzzling, not least because skilled-wage differentials in favor of rich countries contradicts the predictions of much modern growth theory.

A plausible explanation for this puzzle is lower capital intensity of production in poor countries vis-a-vis rich countries. In a neoclassical constant returns to scale aggregate production function, capital and labor are q-complements. That is, an increase in the use of one of these factors raises the marginal product of the other (Acemoglu, 2024). Evidence from long-run economic growth is broadly consistent with this prediction: capital-labor ratios have increased in most industrialized countries in the 20th century, and this was accompanied by growth of labor earnings.[3] Therefore, more capital intensity always increases the marginal product of labor. So long as the wage is proportional to labor productivity, lower capital intensity always decreases wages.

Caselli and Feyrer (2007) in a broad sample of developing countries and developed countries find enormous cross-country variation in capital intensity. Moreover, they find that the relative price of capital is high in poor countries and relative productivity in the capital goods producing sectors is low. What explains this cross-country variation in capital intensity? King and Levine (1993) provide cross-country evidence that lend support to the hypothesis that the level of financial sector development is positively associated with faster rates of economic growth and physical capital accumulation. They find that financial development is a good predictor of the rate of

[3] Wolff (1991) investigates the role of capital intensity in the process of productivity catch-up for G7 countries over the 1870-1979 period. He finds that convergence in capital-labor ratios explains convergence in labor productivity levels.

physical capital formation both before and after controlling for numerous country and policy characteristics.[4]

Against this background, we incorporate credit constraints into the Romer (1990) model of endogenous growth.[5] Romer (1990) viewed technological progress as an increase in the variety of capital goods (horizontal innovation), and showed how this increase could come about as the result of profit-maximizing behavior by entrepreneurial researchers. Specifically, the economy consists of three sectors: a final-goods sector, an intermediate-goods sector, and a research sector. The research sector creates new designs, which take the form of new varieties of intermediate inputs. The research sector sells the exclusive right (patents) to produce a specific variety to the intermediate sector.

We assume that firms in the intermediate sector face higher borrowing costs owing to credit constraints, which in turn increases the marginal cost of capital and the price of the intermediate inputs. As a result, less capital is used by the final-goods producing sector i.e., capital intensity of the economy falls. Since each unskilled worker employed in this sector has less capital to work with, both labor productivity and wages of these workers are lower vis-a-vis rich countries. Furthermore, lower demand for capital from the final-goods sector translates to lower profitability for the R&D sector. Since patents are less valuable, demand for skilled workers and their compensation are lower in poor

[4] Rajan and Zingales (1998) using industry-level data find that better developed financial markets help overcome market frictions that drive a wedge between the price of external and internal finance. Lower costs of external finance facilitate firm growth and new firm formation. Similarly, BØler et al., (2023) provide empirical evidence on firm-level effects of credit constraints. Their results suggest that removal of credit constraints increased labor productivity through reduced misallocation and capital deepening.

[5] Credit constraints are often perceived as one of the most important market frictions, constraining innovation and growth as they hamper the entrepreneurial efforts of local firms (Banerjee and Duflo, 2005; Eckel and Unger, 2024). In the presence of credit constraints, firms face higher borrowing costs which in turn negatively affects innovation activity and productivity. In practice, several factors such as transaction costs, agency costs and asymmetric information can lead to higher borrowing costs (Schiantarelli, 1996).

countries relative to rich countries. This reasoning suggests a possible explanation of the stylized facts related to skilled-wage differential and migration patterns in favor of rich countries that Lucas (1988) observed.

The rest of the paper is organized as follows. In Section 2, we introduce a simplified version of the Romer model and discuss its growth implications. In Section 3, we incorporate credit constraints into this framework and show how the interplay between credit constraints and capital accumulation can help account for the persistent wage differential in favor of rich countries. Section 4 concludes.

2 Basic Setup

The aggregate production function in the Romer model describes how the capital stock, K, and unskilled labor, L_Y, combine to produce output, Y, using the stock of ideas, A:

$$Y = K^{\alpha}(AL_Y)^{1-\alpha}, \tag{2.1}$$

where, $0 \leq \alpha \leq 1$. This production function exhibits constant returns to scale with respect to the capital and labor inputs, and therefore must exhibit increasing returns with respect to all three inputs. The accumulation equations for capital and labor are identical to those for the Solow (1956) model. Capital accumulates as people in the economy forgo consumption at some given rate, s_K, and depreciates at the exogenous rate, δ:

$$\dot{K} = s_K Y - \delta K. \tag{2.2}$$

Labor force is assumed to grow exponentially at some constant and exogenous rate, n:

$$L(t) = L(0)e^{nt}. \tag{2.3}$$

In the Solow (1956) model the productivity term A grows exogenously at a constant rate. In the Romer model, growth in A is endogenized. At the heart of the R&D based growth models is a knowledge production function. According to that function, the rate of production of new knowledge, $\dot{A}$, depends on the amount of skilled-labor (L_A) involved in the production of ideas i.e.,

$$\dot{A} = \bar{\theta} L_A, \tag{2.4}$$

where, $\bar{\theta} = \theta A$, is the rate at which new ideas are discovered or research productivity.

Finally, we need to explain how labor, L, is allocated in this economy. We assume that a constant fraction, $L_A/L = s_R$, of the labor force engages in R&D activity to produce new ideas and the remaining fraction, $(1 - s_R)$, produces output, Y. We assume that the economy starts off with some initial endowments i.e., with K_0 units of capital, L_0 units of labor, and A_0 ideas. This completes our setup of the model.

2.1 Steady-State Growth in the Romer model

Given the above setup it can be easily shown that a balanced growth path exists for this economy, which is defined as a situation in which all variables grow at a constant rate. Along this path, output per worker (y) and the capital-labor ratio (k) grow at the same rate as technology (A): where g_y, g_k, and g_A denote the steady-state growth rate of y, k, and A.[6] Hence, R&D based growth models share the prediction of the neoclassical model that technological progress is the source of sustained growth in per capita income. Therefore, to solve for the steady-state growth rate of per capita income in this economy it suffices to solve for, g_A, which in turn is determined by the knowledge production function. Therefore,

$$g_y = g_k = g_A = \theta L_A. \tag{2.5}$$

Equation(2.5) tells us that the steady-state growth rate of per capita income depends positively on the amount of skilled labor devoted to R&D activity. The model exhibits a "scale effect": a larger economy provides a larger market for an idea raising the return to research. In addition, a larger economy has more potential creators of ideas. This scale effect result is a hall mark of many existing R&D based endogenous growth models, including the important contributions of Grossman and Helpman (1991), and Aghion and Howitt (1992). This result has important policy implications. Policies that permanently increase the amount of skilled labor devoted to R&D - a subsidy that encourages researchers, for example, have a permanent long-run effect on the growth rate of the economy.

[6] The growth rate of output per worker, $g_y = \alpha\left(\dot{k}/k\right) + (1-\alpha)(\dot{A}/A)$. In steady-state, $\dot{k} = 0$. Therefore, $s_k y = (\delta + n)k$. Since y/k is a constant, the growth rate of y should equal the growth rate of k. Thus, in steady-state, $g_y = g_k = g_A$.

3 Microfoundations of the Model with Credit Constraints

The economy consists of three sectors: a final-goods sector, an intermediate-goods sector, and a research sector. The research sector creates new ideas, which take the form of new varieties of intermediate inputs. The research sector sells the exclusive right to produce a specific input to the intermediate sector. The intermediate sector manufactures the capital good and sells it to the final-goods sector, which produces output.

3.1 The final goods sector

The final-goods sector consists of a large number of perfectly competitive firms that combine unskilled labor, L_Y, and a variety of capital goods, x_j to produce a homogeneous output good, Y. We shall normalize the price of the final output, Y, to unity. The production function is specified to reflect the fact that there is more than one intermediate input in the model:

$$Y = L_Y^{1-\alpha} \int_0^A x_j^{\alpha} dj, \tag{3.1}$$

where x_j is the intermediate input j, and A is the number of varieties of the differentiated intermediate inputs available in the economy. The specialized inputs are aggregated in a way familiar from Ethier (1982). In this framework, the stock of knowledge corresponds to the subset of the real line denoting the produced durables for which designs have been invented. Firms in the final-goods sector have to decide how much unskilled labor and intermediate inputs to use in producing output. They do this by solving the profit-maximization problem,

$$\max_{L_Y, x_j} L_Y^{1-\alpha} \int_0^A x_j^\alpha dj - w_Y L_Y - \int_0^A p_j x_j dj, \tag{3.2}$$

where p_j is the rental price for capital good j and w_Y is the wage paid to unskilled labor. The first-order conditions to this problem are:

$$w_Y = (1-\alpha)\frac{Y}{L_Y} \tag{3.3}$$

and

$$p_j = \alpha L_Y^{1-\alpha} x_j^{\alpha-1}, \tag{3.4}$$

where this second condition applies to each capital good j (see Appendix A).[7] The first says that firms hire unskilled labor until its marginal product is equal to the wage, and the second equation says that capital goods are purchased until their marginal product is equal to price charged by the intermediate goods firm.

[7] Physical capital accumulation in the model translates to a higher marginal productivity of unskilled labor, and thus improved real wage (see equation 3.3). That is, capital accumulation boosts worker productivity: two workers equipped with two shovels can dig a hole faster than sharing one shovel.

3.2 The intermediate goods sector

The intermediate sector is composed of an infinite number of firms on the interval $[0, A]$. The differentiated intermediate goods are produced under monopolistic competition. Researchers are motivated by the prospect of monopoly profits to expand resources to discover new varieties of capital goods. Patent protection ensures that no one else can produce their version. We assume that there is free entry into the R&D sector, so that anyone can pay the R&D cost to secure a patent. A firm that has purchased a design rents raw capital and then effortlessly manages to transform each unit of raw capital into a single unit of the intermediate input.

The model includes credit constraints in that, these firms do not have wealth to self-finance production. Thus, production of intermediate inputs requires that entrepreneurs raise funds from outside investors. Moreover, the inventor or producer frequently have better information about the likelihood of success and the nature of the contemplated innovation project than outside investors (asymmetric information). With respect to R&D investment, economic theory advances a variety of reasons why there might be a gap between the external and internal costs of capital (see Hall and Lerner, 2010).[8]

Moreover, in poor countries, firms may lack access to credit, or they may not have access to as much credit as they want given the interest rate, r. We let, $\tau \geq 1$, reflect the magnitude of credit constraints. A firm will invest in capital until its marginal

[8] As pointed out by Rajan and Zingales (1998), industries that require a lot of upfront outside financing (relative to generated cash flow), such as drug and pharmaceuticals (due to R&D costs), are less likely to grow in the presence of credit constraints compared to those industries where credit constraints are not binding. BØler et al.(2023) show that, firms that are intensive in intangible capital may struggle to get access to bank credit. First, due to the nature of intangible capital, a substantial asymmetric information is likely to exist between firms and potential investors. Second, intangible intensive firms often have limited collateral value, which may limit their access to bank loans.

revenue product equals the marginal cost of capital. Therefore, for a credit constrained firm, the implicit cost of capital is, τr. The monopolists in the intermediate sector know what effect they have on p_j. They know that if, they raise their price, the final-goods sector will reduce their consumption. Like any another monopolist, they take this into account. That is, they use their knowledge of the demand curve from the final goods sector above.

Then, the profit maximization problem for the credit constrained intermediate sector is:

$$\max_{x_j} \pi_j = p_j(x_j)x_j - (\tau r + \delta)x_j, \tag{3.5}$$

where $p_j(x_j)$ is the inverse demand function for the intermediate input from the final-goods sector equation (3.4) above.[9]

The first-order condition for any firm j is

$$p_j'(x_j)x_j + p_j(x_j) = \tau r + \delta. \tag{3.6}$$

Profit maximization leads to the familiar outcome of Dixit and Stiglitz (1977) that firms charge prices (for intermediate inputs) that are a constant markup $(1/\alpha)$ over marginal cost of production.[10] Therefore, we have

$$p_j = \left(\frac{1}{\alpha}\right)(\tau r + \delta). \tag{3.7}$$

[9]Output produced by the final-goods sector is used for consumption and investment in "raw capital" goods. Households then rent the raw capital (k_j) out to the intermediate-goods sector at the capital cost, τr, per unit of raw capital.

[10]From equation (3.4) we know that $p_j'(x_j) = (\alpha - 1)(p_j/x_j)$.

This is the price of each capital good. Since all varieties enter symmetrically in equation (3.1) and production costs of all varieties are the same, $p_j = p$. Equation (3.7) tells us that the higher borrowing cost due to credit constraints, τr, by increasing the marginal cost of capital increases the price of all intermediate inputs p_j. This causes demand for all intermediate inputs to fall in the same proportion (see equation 3.4). Thus, capital intensity in the final-goods sector falls. As each unit of unskilled labor, L_Y, has less capital to work with, both labor productivity and wages of unskilled workers, w_Y, are lower in credit-constrained economies.

If we substitute for p_j from equation (3.7) into equation (3.4), we can determine the output produced by each monopolist,

$$x_j = \left(\frac{\alpha^2}{\tau r + \delta} \right)^{1/1-\alpha} L_Y. \tag{3.8}$$

Note that, because price exceeds marginal cost, the quantity x_j is smaller than it would be if intermediate goods were priced at marginal cost.[11] That is, in the decentralized economy, the quantity demanded is smaller. The gap generates a static efficiency loss from monopoly. Thus, when producers have market power, they produce less than the socially optimal amount. Moreover, as all varieties of intermediate inputs enter symmetrically in the production function (and production costs are identical), each

[11] The quantity of intermediate goods that a hypothetical social planner would like produced is, $(\alpha/\tau r + \delta)^{1/1-\alpha} L_Y$, which is the amount that would be demanded if price equals the marginal cost of production.

monopolist earns the same profit,[12]

$$\pi = \alpha(1-\alpha)\frac{Y}{A} \quad \forall i. \tag{3.9}$$

Finally, market clearing implies that the total demand for capital from the intermediate goods sector must be equal to the total stock of capital available in the economy,

$$\int_0^A x_j d_j = K. \tag{3.10}$$

Since all varieties of intermediate inputs enter symmetrically in the production function, in equilibrium $x_j = x$ for all j. This implies that, $Ax = K$. Substituting for $'x'$ in equation (3.1) gives us,

$$Y = K^{\alpha}(AL_Y)^{1-\alpha}, \tag{3.11}$$

where equation (3.11) is the aggregate production function in the Solow-Romer model.

3.3 The research sector

Ideas in this model are designs for new capital goods. At a point in time, the technology exists to produce A varieties of intermediate inputs. An expansion of the number A requires a technological advance. New invention requires purposive effort in the form

[12]Substituting equation (3.7) in equation (3.5) gives us, $\sum_{j=1}^{A} \pi_j = (1-\alpha)\sum_{j=1}^{A} p_j x_j$. Plugging p_j from equation (3.4) given us the aggregate profit earned by the intermediate-goods sector, $\sum_{j=1}^{A} \pi_j = \alpha(1-\alpha)Y$. Therefore, each monopolist earns the same profit, $\pi = \alpha(1-\alpha)(Y/A)$.

of R&D. Entrepreneurial researchers hunt for new designs because of the financial rewards that can be earned by innovating. Successful designs receive a patent from the government that gives them the exclusive right to produce with their invention. These designs are instructions that explain how to transform a unit of raw capital into a unit of new capital good.

The question is, what is the price of a patent for a new design? The answer (assuming no uncertainty and perfect foresight) is the present discounted value of the profits to be earned.[13] That is, the flow of monopoly profits provides the incentive for invention. Therefore, the price of a patent (P_A) is,

$$P_A(t) = \int_t^{\infty} \pi(s) e^{-\int_t^s \tau r(u) du} ds, \tag{3.12}$$

where $\pi(s)$ is the profit flow at date s, τr is the interest cost for a credit constrained firm between t and s, and u is a dummy variable. Differentiating equation (3.12) with respect to time (see Appendix B), we get

$$\tau r(t) P_A(t) = \pi(t) + \dot{P}_A(t). \tag{3.13}$$

The left-hand side of the equation is the interest earned from purchasing a unit of raw capital; the two terms on the right-hand side are the profits plus capital gain or loss that results from the change in the price of the patent, $P_A(t)$. Since the interest rate,

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[13] R&D firms face a two-stage decision process. First, they decide whether to devote resources (hire skilled workers) to invent a new design. If the present value of profits is as large as the R&D cost, firms will undertake R&D expenditures. In the second stage, they determine the price at which to sell the patent to the intermediate-goods sector. The competitive R&D sector sets the price, P_A, to extract the present discounted value of the intermediate sectors monopoly profits.

τr, is a constant in equilibrium and from equation (3.9) we know that profits grow at a constant rate, $n > 0$, we can rearrange equation (3.13) as,[14]

$$P_A(t) = \frac{\pi(t)}{\tau r - n}. \tag{3.14}$$

This equation (the present discounted value of profits) gives us the price of patents along the balanced growth path. If the discount rate, τr, is high, then people discount the future a lot, so the stream of profits from a new innovation is not as valuable. Hence innovation effort will be lower in this case. As a result, both the demand for patents and the price of patents are lower in the presence of credit constraints, $\tau r > r$. Since, profits earned by these firms are eventually extracted by the R&D sector (profits compensate the inventors for their effort), lower value of patents creates less market incentives for R&D activity. Therefore, demand for skilled-workers, L_A, falls, lowering the return to skill in poor countries.

3.4 Share of the labor force engaged in R&D

So far we have assumed that share of the labor force engaged in R&D activity, s_R is constant. We now derive the share of labor employed by the R&D sector in the decentralized economy. Labor market clearing implies that the total amount of available labor has either to be employed in the final-goods sector or in the R&D sector. Furthermore, we know that wages in all sectors have to equalize, such that, $w_Y = w_A$,

[14] We know from equation (3.4) that the price of capital, $p_j = (1/\alpha)(\tau r + \delta)$, is proportional to the marginal product of capital, $\alpha(Y/K)$. Along the balanced growth path, the growth rate of output equals the growth rate of capital. Therefore, output to capital ratio is a constant.

otherwise one sector would not be able to attract any workers.[15]

$$\bar{\theta}\left(\frac{\pi}{\tau r - n}\right) = (1-\alpha)\frac{Y}{L_Y}. \tag{3.15}$$

Substituting for $\bar{\theta}$ from equation (2.4) and π from equation (3.9) gives,

$$\frac{\alpha g_A}{\tau r - n} = \frac{L_A}{L_Y} = \frac{s_R}{1 - s_R}. \tag{3.16}$$

Solving equation (3.16) for s_R, gives

$$s_R = \frac{1}{1 + \dfrac{\tau r - n}{\alpha g_A}}. \tag{3.17}$$

The higher the discount rate that applies to current profits, $\tau r - n$, the lower the fraction of the labor force engaged in R&D activity. This is because, with higher borrowing costs, patents are less valuable. Therefore, demand for skilled labor, L_A, is lower in this model.[16] On the other hand, the faster an economy grows (higher, g_A), the greater the fraction of the population that works in the research sector.

Finally, production in the model is characterized by increasing returns to scale. Therefore, all factors of production cannot be paid their marginal product. Therefore,

[15] Labor working in the final-goods sector earn a wage that is equal to their marginal product, $w_Y = (1-\alpha)(Y/L_Y)$. Likewise, labor working in the R&D sector earn a wage that is equal to their marginal product, $w_A = \bar{\theta}P_A$. With individuals free to move between sectors, it must be that, $\bar{\theta}\,(\pi/\tau r - n) = (1-\alpha)(Y/L_Y)$, in equilibrium.

[16] According to the UNESCO Science Report (2021), high-income countries share of global researchers was 60.24% while low-income countries share was a mere 0.21% in the year 2018. Researchers per million inhabitants in high-income countries was 4301.1 in 2018 while it was 45.1 in low-income countries. R&D personnel in the report refers to all persons engaged directly in R&D, as well as those providing direct services for the conduct of R&D, such as R&D managers, technicians, etc.

owners of capital are paid less than their marginal product, $\alpha^2(Y/K) < \alpha(Y/K)$, in order to compensate researchers for the creation of new designs.

4 Conclusion

The neoclassical model predicts that poor countries should have a higher rate of return to skilled labor relative to rich countries. In reality, skilled workers earn less (adjusted for purchasing power), rather than more, in poor countries. Furthermore, both physical and human capital flow toward rich countries, as does unskilled labor. Why is this the case?

We introduce credit constraints into a standard endogenous growth model. We show how the interplay between higher borrowing costs and capital accumulation can help explain the persistent skilled-wage differential in favor of rich countries. Specifically, higher borrowing cost (by raising the marginal cost of production) increases the price of all varieties of capital goods in our model. As a result capital intensity of the economy falls, lowering both labor productivity and return to unskilled labor. Since the demand for capital is lower, R&D activity is also less profitable. This in turn explains why both demand for skilled labor and return to skill are lower in poor countries. Responding to this wage-rate differentials, skilled workers naturally tend to move toward economies that have high ratios of capital to labor because of a high intrinsic level of productivity and wages. In fact, for much of the 20th century, capital accumulation in the industrialized world went hand-in-hand with rising wages. Therefore, international migration has occurred along expected lines.

Our analysis points to important policy issues for poor countries. Even if the problems associated with incomplete appropriability of the return to R&D activity are solved using intellectual property protection, there is often a wedge, sometimes large, when financial markets are underdeveloped. Industries that require a lot of upfront outside financing, such as R&D activity, will be less likely to grow in the presence of capital market imperfections. Financial sector reforms that improve the functioning of the credit market would potentially have a significant long-run impact on capital accumulation, labor productivity, and standard of living in poor countries. This conclusion of course does not rule out an important role for social infrastructure, such as, the quality of political and legal institutions, corruption, government policies related to education and research, tax policies, etc in the growth process (Hall and Jones, 1999). Rich countries are rich precisely because they have found ways to limit the extent of diversion in their economies.

Declarations

The authors have no relevant financial or non-financial interests to disclose. The authors have no competing interests to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

Appendix A Marginal product of capital

To solve the maximization problem of the firm, we need to employ the *calculus of variations.*[17] A functional $S : \mathcal{C} \to \mathbb{R}$ is a correspondence from a space of functions $\mathcal{C}$ to real numbers $\mathbb{R}$. We usually take $\mathcal{C}$ to be the normed linear space $\mathcal{D}_1(a, b)$ consisting of continuously differentiable functions on $[a, b]$ with either the strong norm $||f|| = \max_{t\in[a,b]} |f(t)|$ or the weak norm $||f|| = \max_{t\in[a,b]} |f(t)| + \max_{t\in[a,b]} |f'(t)|$. The notion of a derivative of a functional S at $f \in \mathcal{C}$ is given by the following definition.

Definition 1. *Let $S : \mathcal{C} \to \mathbb{R}$ be a functional defined on a normed linear space $\mathcal{C}$. Let $f \in \mathcal{C}$ and $\phi \in \mathcal{C}$ and such that $f + \epsilon\phi \in \mathcal{C}$ for all real numbers ϵ sufficently small. Then the first variation (or the Gâteaux derivative) of S at f in the direction of ϕ is defined as*

$$\delta S(f, \phi) = \left[\frac{d}{d\epsilon} S(f + \epsilon\phi)\right]_{\epsilon=0},$$

provided the derivative exists. The direction ϕ for which $\delta S(f, \phi)$ exists is called an admissible variation at f.

The following theorem gives the necessary conditions for a functional S to have a local extremum at $f = \gamma$.

Theorem 1. *If the functional $S : \mathcal{C} \to \mathbb{R}$ has a local extremum at $f = \gamma$ relative to the norm $|| \cdot ||$, then the Gâteaux derivative $\delta S(f, \phi) = 0$ for all admissible variations ϕ.*

We now apply this to the functional $\pi : \mathcal{D}^1[0, A] \to \mathbb{R}$ given as in equation (3.2).

$$\pi(x) = L_Y^{1-\alpha} \int_0^A x_j^\alpha dj - w_Y L_Y - \int_0^A p_j x_j dj, \tag{A1}$$

[17] See Gelfand and Fomin (2000) for an overview.

where π is a functional which takes a continuously differentiable function x on $[0, A]$ as input and returns a real number. To comptute the derivative of π, we take a function $\phi \in \mathcal{D}^1[0, A]$ such that $x + \epsilon\phi \in \mathcal{D}^1[0, A]$. Then,

$$\begin{aligned} \delta\pi(x, \phi) &= \left[\frac{\mathrm{d}}{\mathrm{d}\epsilon}\pi(x + \epsilon\phi)\right]_{\epsilon=0} \\ &= \left[\frac{\mathrm{d}}{\mathrm{d}\epsilon}\left(L_Y^{1-\alpha}\int_0^A [x_j + \epsilon\phi_j]^\alpha dj - w_Y L_Y - \int_0^A p_j[x_j + \epsilon\phi_j]dj\right)\right]_{\epsilon=0}. \end{aligned} \tag{A2}$$

Exploiting the Leibniz's integral rule, we get

$$\delta\pi(x, \phi) = \left[L_Y^{1-\alpha}\int_0^A \alpha[x_j + \epsilon\phi_j]^{\alpha-1}\phi_j dj - \int_0^A p_j\phi_j dj\right]_{\epsilon=0}. \tag{A3}$$

$$\delta\pi(x, \phi) = \int_0^A \alpha L_Y^{1-\alpha} x_j^{\alpha-1}\phi_j d_j - \int_0^A p_j\phi_j dj. \tag{A4}$$

Finally, from Theorem 1, the stationary points of functionals are found by setting $\delta\pi(x, \phi)$ to zero, i.e.,

$$\int_0^A \left[\alpha L_Y^{1-\alpha} x_j^{\alpha-1} - p_j\right]\phi_j d_j = 0. \tag{A5}$$

Since this must be true for all ϕ, it is sufficient that the integrand is identically equal to zero (this means it is zero for all $'j'$). This yields equation (3.4) in the text.

Appendix B Valuation of a Patent

From equation (3.12) we know that,

$$P_A(t) = \int_t^{\infty} \pi(s) e^{-\int_t^s \tau r(u)du} ds, \tag{B1}$$

where $\pi(s)$ is the profit flow at date s and τr is the interest rate between times t and s for a credit constrained firm and u is a dummy variable. We flip the limits of integration and take a, a constant, instead of ∞ as the lower limit of integration in equation (B1). We shall later take the limit as $a \to \infty$ to get back the improper integral. Therefore,

$$P_A(t) = -\int_a^t \pi(s) e^{-\int_t^s \tau r(u)du} ds. \tag{B2}$$

We now exploit Leibniz's rule for differentiation of a definite integral.[18] We get,

$$-\dot{P}_A(t) = \pi(t) e^{-\int_t^t \tau r(u)du} + \int_a^t \pi(s) e^{\int_s^t \tau r(u)du} \tau r(u) ds. \tag{B3}$$

The first term on the right-hand side of equation (B3) is, $\pi(t)$. The second term on the right-hand side is the derivative with respect to t of our function, $f(t) = \pi(s)e^{\int_s^t \tau r(u)du}$.

[18] The Leibniz formula if the limits of integration are functions of x and $f(x, y)$ is a function of two variables that can be integrated with respect to t and differentiated with respect to x: $F'(x) = \int_{a(x)}^{b(x)} f_x(x,t)dt + f(x, b(x))b'(x) - f(x, a(x))a'(x)$. If $a(x) = a$ is a constant and $b(x) = x$, the rule simplifies to: $F'(x) = f(x, x) + \int_a^x f_x(x, t)dt$.

Re-write equation (B3) as:

$$-\dot{P}_A(t) = \pi(t) + \tau r(t)\int_a^t \pi(s)e^{\int_s^t \tau r(u)du}ds. \tag{B4}$$

Now flip the limits of integration in equation (B4) to get,

$$-\dot{P}_A(t) = \pi(t) - \tau r(t)\int_t^a \pi(s)e^{\int_s^t \tau r(u)du}ds. \tag{B5}$$

We can now take the limit as $a \to \infty$ in order to obtain,

$$-\dot{P}_A(t) = \pi(t) - \tau r(t)\int_t^\infty \pi(s)e^{\int_s^t \tau r(u)du}ds. \tag{B6}$$

Finally, substituting $P_A(t)$ from equation (B1) into (B6) gives,

$$-\dot{P}_A(t) = \pi(t) - \tau r(t)P_A(t). \tag{B7}$$

Re-arranging equation (B7) yields the result reported in equation (3.13),

$$\tau r(t)P_A(t) = \pi(t) + \dot{P}_A(t). \tag{B8}$$

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