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Intellectual Property Rights, Human Capital and the Incidence of R&D Expenditures

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Abstract

Numerous studies predict that developing countries with low human capital may not benefit from the strengthening of intellectual property rights. The authors extend an influential theoretical framework to highlight the role of intellectual property rights in the process of innovation and structural change. The resulting theory is consistent with a stylized fact that appears in the data, namely that countries with poor intellectual-property protection may accumulate human capital without a corresponding increase in research and development investment as a share of national income. The model predicts that without minimum intellectual-property protection, additional education may result in more imitation rather than innovation. The preponderance of the econometric evidence presented in this paper suggests that interactions between human capital and intellectual property rights determine global patterns of research and development effort, and intellectual property rights tend to raise the effect of education on the incidence of research and development.

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1 Introduction and Related Literature

The quality of institutions and their impact on economic development is an important field in economic inquiry, and the literature on intellectual property rights (IPRs) and innovation can be viewed as a sub field. Much of the existing literature on intellectual property rights predicts that these institutions may have different (perhaps negative) effects on developing economies than on rich countries (e.g. Higino-Schneider 2005; Maskus 2000; Helpman 1993; Grossman and Lai 2005). In an extension of the work of Aghion and Howitt (1992), we model interactions between the institutional setting and innovation in the presence of costly imitation. We derive a set of predictions about the relationship between the level of research and development expenditures (R&D), human capital and IPRs. The subsequent econometric evidence rejects linear and separable functional forms, which is consistent with the model predictions. The evidence thus suggests that poor countries may accumulate human capital without a corresponding increase in the incidence of R&D as a share of national income without strengthening IPRs.

One longstanding strand of the literature on institutions and innovation focuses on the optimal design of IPRs, taking into account tradeoffs between the provision of information that can help spur future innovations while providing inventors an institutional solution to their appropriability problem. Nordhaus (1969, Chapter 5) provided an early contribution, which focused on the policy maker's concern about raising social welfare through the design of IPRs. A more recent literature on the optimal design of IPRs is rooted in the idea of cumulative or sequential innovation, whereby new innovations produce the ideas for future innovations. Hopenhayn et al. (2006) is an example of recent theoretical treatments in this vein. Throughout this literature, firms are characterized only in terms of the profits received from innovations, and the optimal patent design depends on the breadth and scope of innovation. However, the decision to innovate or imitate is not modeled explicitly.

An important effort to incorporate the decision to imitate by firms is Gallini (1992), who considers the effect of costly imitation on the optimal patent length. However, in this framework there is no imitation when the patent length is optimal. This is due to uniformity of patent lengths within a class of patents that supposedly fits all innovations, when in fact the optimal patent length depends on technological parameters that vary across goods. More recently, Jim and Troege (2006) proposed a model in which firms decide simultaneously how much to innovate and imitate (through a spillover-absorption coefficient) in a Cournot setting, but institutions play no role in shaping investment decisions. We depart from previous literature by taking patent length as given and allowing simultaneously costly imitation and innovation. In addition, we explicitly model the role of IPRs in determining the incentives of firms to choose between innovation and imitation.

There is a literature on the role of IPRs in economic development. This literature has mainly

focused on North-South patterns of trade associated with different IPR regimes and the associated welfare gains or losses (Grossman and Helpman 1991; Helpman 1993). Zigic (1998) explores situations where leakages due to imperfect IPRs might produce counter-intuitive results. For example, spillovers might make the strengthening of IPRs in the South beneficial for the welfare of developing economies as R&D in the North rises, with subsequent positive spillovers for the South in the form of profit leakages from profits driven by scale. An interesting feature of most of these models of international technology diffusion is that developing countries are characterized as only having firms involved in imitation, and the firm-level decision about whether to innovate or imitate is ignored. Firms in the developed North decide how much to spend in R&D, but the option of imitation is not considered, and thus these models are silent with respect to economic structure within countries. Grossman and Lai (2005) extend traditional models by considering a two-country setup with costless imitation, enforcement and national treatment of patents. Unlike other models, in Grossman and Lai (2005) Southern countries are allowed to innovate. They study optimal patent policies for countries engaged in trade. Their main results establish that the benefits from IPRs rise with market size and human capital. Thus, considering that Northern countries have larger markets and greater capacity to innovate, it follows that they have stronger incentives to strengthen IPRs compared to Southern countries. However, the enforcement of patents is modeled as a constant probability that affects the instantaneous monopolistic profits; neither risk nor the process of enforcement of IPRs is considered.

More recently, Branstetter and Saggi (2009) explored the relationship between IPRs and foreign direct investment (FDI). In their model, the South imitates, but imitation is endogenously determined as is FDI in a North-South model. The strengthening of IPRs in the South reduces imitation and FDI increases. More importantly, FDI gains more than offset the decline in imitation. In a previous model proposed by Chen and Puttitanum (2005), a Southern firm is allowed to imitate a foreign (Northern) product while another domestic firm can carry out R&D activities facing domestic competition. These authors study the optimal IPR regime through the course of development. They model IPRs as the ability to imitate in an static setting without explicitly modeling IPR structure. Their main finding is that optimal IPRs follow a U-shaped function with respect to income.

This article proposes a new modeling approach, based on Aghion and Howitt (1992), to understand observed patterns of R&D shares in national income across countries. The theoretical contribution entails a model of two sectors that operate simultaneously with costly imitation and innovation, where firms decide endogenously whether to participate in innovative or imitative activities. In contrast with the North-South literature, our model is a closed economy model. This allows us to focus on and carefully model the enforcement of IPRs. The gains of modeling an open economy would complicate the mathematical exposition and would change the focus of our model,

which is to model the interactions between IPRs and human capital. The endogenous allocation of firms embodying human capital across sectors results in endogenous aggregate innovation and imitation rates. We derive a set of results for the steady state equilibrium of our model; that is, for constant allocations of human capital across sectors.

In contrast to Aghion and Howitt's seminal contribution, we omit transitional dynamics. In equilibrium, the enforcement of IPRs, through monitoring effort and imposition of fines, helps determine the allocation of labor across these two sectors by affecting the risk-adjusted relative discount rate for innovators and imitators as well as the stream of profits. The discount rate affects the present value of labor productivity, which is also affected by the fees and compensations derived from the enforcement of the IPRs. A second result is that certain conditions are required to ensure that an increase in the endowment of human capital increases the share of labor devoted to R&D activities. This result is driven by inter-sector human capital mobility, and human capital will move into innovation only if IPRs are strong enough. Perhaps more importantly, the model predicts that aggregate R&D shares will depend on complex interactions between the quality of IPRs and human capital endowments. In spite of this complex relationship, the model predicts that IPRs will have a positive effect on the incidence of R&D expenditures, and, under fairly nonrestrictive assumptions, the marginal effect of human capital depends on IPRs. Hence, with lax IPRs, the accumulation of human capital may not raise the incidence of R&D.

The model yields a testable prediction, namely that the share of R&D expenditures in GDP is a non-linear but positive function of IPRs and is generally a positive function of human capital. The existing empirical literature, however, has focused exclusively on log-linear functions of R&D determinants (e.g., Varsakelis 2001; Chen and Puttitanum 2005). We provide empirical tests of functional linearity and separability of human capital and IPRs in an R&D model. The preponderance of the evidence supports the theoretical model.

The rest of the paper is organized as follows. Section 2 presents the theoretical model. Section 3 discusses the empirical methodology, and section 4 discusses the econometric results. Section 5 concludes.

2   The Model

Our model is an extension of Aghion and Howitt (1992). However, instead of competition between R&D activities and production, we present a trade-off between R&D and illegal imitation. There is one input, human capital, which is allocated between these two activities. Each person has one unit of human capital and there are E_T total units of human capital in the economy. Each person is an entrepreneur who sets up a firm and decides whether she will use her unit of human capital in R&D or imitation activities, which can be interpreted as patent infringement.

As in Aghion and Howitt (1992), innovation follows a Poisson process with a flow probability parameter λ and exhibits constant returns to scale in the human capital dedicated to R&D. Illegal imitation follows a Poisson process with flow probability parameter parameter μ and also exhibits constant returns to scale in employed human capital. The randomness represents in one case the success rate of an innovation, and in the other the success rate of reverse engineering per unit of human capital. Given the additivity property of Poisson processes and the constant returns to scale, for each sector the resulting stochastic processes will also follow a Poisson distribution with a parameter that depends on the original flow probability and the human capital allocated to each sector. One crucial difference between the two sectors is that in the innovation sector each innovator must incur a fixed cost of infrastructure of magnitude K.[1]

The government enforces patent rights, and, for the sake of clarity, patents are infinitely lived. We assume that the enforcement process follows a Poisson distribution with flow probability p, which represents the sampling probability for any given imitating firm. There are also constant returns to scale in government expenditure, x, which increases the efficacy of the enforcement process. The government imposes a fine of size F on imitating firms that have not paid royalties. For the sake of simplicity, we assume that the fine is transferred to the innovating firm, but the model predictions would be unaffected if the transfer is a fraction of the fine. Another interpretation is that F is a court-mandated transfer from the imitating to the innovative firm.

With respect to industrial organization, we assume monopolistic rents for a firm that has been successful in developing R&D activities and whose invention has not been imitated. Once a firm's invention has been imitated, the imitating and innovative firms compete as a Cournot duopoly. We assume Bertrand competition with the successive entry of imitating firms, given similar cost structures among them. These assumptions ensure that there is only one profitable imitating firm.

We further assume that a monopolistic firm enjoys an instantaneous monopolistic rent, Π^M. In the case of Cournot competition, both firms get an instantaneous duopolistic rent of Π^D. Finally, the risk free interest rate in the economy is denoted by r.

2.1 Labor market equilibrium

In equilibrium, the wage or income of the firm or entrepreneur is the same across sectors. Let V represent the value of an invention. The wage (income) paid to the innovator ($R\&D$) equals the expected value of one hour of research:

$$W_{RD} = \lambda \cdot V \tag{1}$$

Analogously, in the imitation sector the wage will be the expected value of one hour spent

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[1] Imitation might also entail costs in infrastructure, but they tend to be smaller in relative terms than the cost of innovation. See, for example, Mansfield et.al. (1981).

in reverse engineering activities. Given that a product can be profitably imitated only once, the marginal product of human capital in this sector is:

$$W_I = \lambda \cdot I \tag{2}$$

where I represents the value of an illegal imitation.

In equilibrium, wages are equalized across sectors and the labor market clears:

$$W_{RD} = W_I \tag{3}$$

and

$$E_{RD} + E_I = E_T \tag{4}$$

where E_{RD}, E_I, and E_T stand for the human capital employed in the R&D sector, imitating sector and total human capital respectively. Thus, by using (3), we reduce equations (1) and (2) to just one equation. Equation (4) completes a system of two equations and two unknowns, E_{RD} and E_I, because V and I can be expressed as functions of exogenous parameters and E_{RD} and E_I, as shown in the following section.

2.2 Expected value of innovation and imitation

With constant returns to scale in both sectors, the rates of success for each sector are given by:

$$Rate(innovation) = \lambda \cdot E_{RD}$$
$$Rate(illegal\_imitation) = \mu \cdot E_I$$

Note that in spite of the constant flow probabilities, economy wide (aggregate) innovation and imitation stochastic processes are determined in equilibrium by the human capital allocated to each activity.

The respective Poisson processes are parametrized with those rates, and the expected present value of profits for firms in the R&D sector (characterized by either monopolistic or duopolistic rents) can be written as follows:

$$V = \int_0^\infty e^{-rt} \pi^M e^{-\lambda E_{RD} t} e^{-\mu E_I t} dt + \int_0^\infty \mu E_I e^{-\mu E_I t} \int_t^\infty e^{-rv} \pi^D e^{-\lambda E_{RD} v} e^{-\mu E_I (v-t)} e^{-px(v-t)} dv dt$$

$$+ EPV(F) - K \tag{5}$$

The first two terms in (5) correspond to the expected present value from monopolistic and duopolistic profits respectively. In these two terms, profits are weighted by the probability of successful innovations, imitations and enforcement. In the first term, the higher the values of λ and μ, the lower the expected value of the monopolistic profits as the emergence of successful innovation or imitation will end this stream of profits. In contrast, the second term, contains two effects. The first is analogous to the one already discussed for monopolistic profits, hence part of this second term (within the right integral) decreases with λ and μ. But there is a second effect whereby expected present value of R&D partially increases with μ as the likelihood of imitation raises the probability of a stream of duopolistic profits.

In sum, when the probability of a new innovation is high, existing innovations become obsolete and thus monopolistic profits decline. When the probability of imitation increases, monopolistic profits also decline, but the expected value of duopolistic profits partially increases with the probability of duopolistic competition, but also partially declines given that a second imitation ends duopolistic competition. Finally, note that the flow of duopolistic profits are conditioned by the existence of a previous imitation and the presence of enforcement, px, hence the second term also decreases with px.

The third and fourth terms in (5) correspond to the expected present value of the fine or transfer (EPV(F)) minus the fixed cost of R&D infrastructure, K. The solution of the previous integrals show more clearly these effects:

$$V = \frac{\Pi^M}{r + \lambda \cdot E_{RD} + \mu \cdot E_I} + \frac{\Pi^D \mu \cdot E_I}{(r + \lambda \cdot E_{RD} + \mu \cdot E_I + px)(r + \lambda \cdot E_{RD} + \mu \cdot E_I)} + EPV(F) - K \quad (6)$$

Equation (6) corresponds to the expected present value of the income flow of a firm in the R&D sector discounted by a risk-adjusted interest rate for the case of monopolistic and duopolistic profits.

A firm in the imitation sector faces the possibility of replacement of an innovation by a new innovation or imitation, and the possibility that the stream of profits will be halted by the enforcement of intellectual property rights, which we model as Poisson process with rate px. If the firm is caught imitating without paying royalties, the government imposes a fine or transfer F. Thus, the expected discounted flow of profits of the imitating firm can be expressed as follows:

$$I = \int_0^\infty \mu E_I e^{-\mu E_I t} \int_t^\infty e^{-rv} \pi^D e^{-\lambda E_{RD} v} e^{-\mu E_I (v-t)} e^{-px(v-t)} dv dt$$
$$-F \int_0^\infty \mu E_I e^{-\mu E_I t} \int_t^\infty e^{-rv} px \cdot e^{-pxv} e^{-\lambda E_{RD} v} e^{-\mu E_I (v-t)} dv dt \tag{7}$$

The first term corresponds to the duopolistic profits, while the second term corresponds to the expected present value of the fine or transfer imposed on imitating firms when property rights are enforced. The enforcement rate, px, has two effects on the expected present value of the fine (transfer). On the one hand it increases its present value by increasing the probability of occurrence of a successful enforcement, but on the other hand it decreases the expected value by reducing the probability of a duopoly and hence the possibility of having to pay the fine. These two effects can be seen more clearly in the second term of equation (8), which is derived by solving the previous integrals:

$$I = \frac{\Pi^D \mu \cdot E_I}{(r + \lambda \cdot E_{RD} + \mu \cdot E_I + px)(r + \lambda \cdot E_{RD} + \mu \cdot E_I)} - \frac{F \cdot \mu \cdot E_I \cdot px}{(r + \lambda \cdot E_{RD} + \mu \cdot E_I + px)^2} \tag{8}$$

This equation corresponds to the expected duopolistic profits of a firm in the imitation sector, discounted by a risk-adjusted interest rate, minus the expected value of the fine (transfer) for illegal imitation. From (8), we derive an expression of the expected present value of the transfer received by the innovating firm:

$$EPV(F) = \frac{F \cdot \mu \cdot E_I \cdot px}{(r + \lambda \cdot E_{RD} + \mu \cdot E_I + px)^2}$$

2.3 Equilibrium

Wages or entrepreneur's incomes are equalized across sectors in equilibrium. Considering that the expected wages depend on the expected value of inventions and imitations, the wage equalization condition can be re-written as follows:

$$\frac{\Pi^M}{r + \lambda \cdot E_{RD} + \mu \cdot E_I} + \frac{\Pi^D \mu \cdot E_I}{(r + \lambda \cdot E_{RD} + \mu \cdot E_I + px)(r + \lambda \cdot E_{RD} + \mu \cdot E_I)} + EPV(F) - K$$
$$= \frac{\Pi^D \mu \cdot E_I}{(r + \lambda \cdot E_{RD} + \mu \cdot E_I + px)(r + \lambda \cdot E_{RD} + \mu \cdot E_I)} - \frac{F \cdot \mu \cdot E_I \cdot px}{(r + \lambda \cdot E_{RD} + \mu \cdot E_I + px)^2}$$

which reduces to:

$$\frac{\Pi^M}{r + \lambda \cdot E_{RD} + \mu \cdot E_I} + 2\frac{F \cdot \mu \cdot E_I \cdot px}{(r + \lambda \cdot E_{RD} + \mu \cdot E_I + px)^2} = K \tag{9}$$

Thus, equation (9) implicitly defines E_{RD} and E_I.[2]

2.4 Comparative statics

Equilibrium across the two sectors requires the following assumptions:

Assumption 1. *The relationship between the fixed cost of R&D, K, profits with zero innovation, and profits with zero imitation must be the following:*

$$\frac{\Pi^M}{r + \mu \cdot E_T} + 2\frac{F \cdot \mu \cdot E_T \cdot px}{(r + \mu \cdot E_T + px)^2} > K > \frac{\Pi^M}{r + \mu \cdot E_T}^M$$

We also assume that there is no waste of public resources. This implies that the monitoring sampling rate must be smaller that the effective rate of innovation plus imitation:

Assumption 2. *The monitoring sampling rate is smaller than the effective rate of innovation plus imitation.*

$$\mu \cdot E_T > px$$

For the sake of clarity regarding the effect of IPRs on the marginal effect of human capital accumulation on the incidence of R&D, the innovation arrival rate is set to be equal to the imitation arrival rate.

Assumption 3. $\lambda = \mu$

To simplify the proof of the propositions discussed below we implicitly differentiate the equilibrium condition (9) with respect to the relevant variables imposing $\lambda = \mu$ and the equilibrium condition $E_{RD} + E_I = E_T$, after these steps in some cases we use again the equilibrium condition to simplify the resulting expressions.

From the model we derive the following set of propositions and corollaries:

Proposition 1. *A reduction in the risk-free discount rate increases the share of the labor force in innovation activities.*

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[2]In the determination of the innovation and imitation values we considered one complete sequence of events. This sequence of events can be repeated endlessly. Thus, the more general innovation and imitation values will be $V' = V \cdot \left(1 + \frac{1}{r(T^*)} + \frac{1}{r(T^*)^2} + \frac{1}{r(T^*)^3}....\right)$. The same will happen with $I' = I \cdot \left(1 + \frac{1}{r(T^*)} + \frac{1}{r(T^*)^2} + \frac{1}{r(T^*)^3}....\right)$. Once the innovation and imitation values are equalized, the factors associated with the repetitions of the sequence will cancel each other out.

Proof. By implicitly differentiating equation (9) with respect to r, we obtain:[3]

$\frac{\partial E_{RD}}{\partial r} = \frac{\Omega}{2\mu px F r_M}$

with $\Omega = 2\Pi^M r_F + 2\mu px F(E_T - E_{RD}) - K(2r_F r_M + r_F^2)$

$r_M = r + \mu E_T$

$r_F = r_M + px,$

Where r_M is the risk adjusted discount rate of the monopolistic profits of innovators, and r_F is the risk adjusted discount rate of imitator's profits. The equilibrium condition implies that $\Omega < 0$, and therefore $\frac{\partial E_{RD}}{\partial r} < 0$. □

The previous proposition is consistent with existing literature that highlights the effect of a low interest rate, which increases the present value of monopolistic profits thus increasing the incentives to innovate. In our model with two sectors this result is no longer obvious. A decline of the discount rate increases the present value of profits in both innovative and imitative activities, with the effect on the former being larger than on the latter, thereby moving workers towards the innovation sector.

Proposition 2. *An increase in the sampling rate, p, or in the government expenditure, x, or in the fine, F, increases the share of the labor force allocated to R&D activities.*

Proof. The proof is obtained by implicitly differentiating equation (9) with respect to F:

$\frac{\partial E_{RD}}{\partial F} = \frac{2\mu px E_I r_M}{2\mu px F r_M} = \frac{E_I}{F}$

Given that the share of workers in the imitation sector is greater or equal than zero then $\frac{\partial E_{RD}}{\partial F} > 0$.

By the same token:

$\frac{\partial E_{RD}}{\partial px} = \frac{2\Pi^M r_F + 2F\mu E_I r_M - 2K r_F r_M}{2\mu px F r_M}$

The equilibrium condition implies that the numerator is positive, and thus $\frac{\partial E_{RD}}{\partial px} > 0$. Indeed, the derivative simplifies to:

$\frac{\partial E_{RD}}{\partial px} = \frac{2\Pi^M r_F + 2F\mu E_I r_M - 2K r_F r_M}{2\mu px F r_M} = \frac{E_I(E_T\mu - px + r)}{px(E_T\mu + px + r)}$, which under Assumption 2 is clearly positive. □

Corollary 1. *Depending on the parameters, increases in the effective sampling rate, px, or the fine, F, can have equivalent effects on the incidence of R&D.*

Proof. The results are derived from the following inequalities and assumption 1. A marginal change in the fine will have a larger effect on the allocation of human capital to R&D than a marginal increase in the sampling probability as long as the following inequalities hold:

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[3]This implicit differentiation implies differentiating both sides of the equilibrium condition with respect to the variable of interest. E_{RD} should be considered a function of the parameters of the model. And as explained in the previous paragraph this should be done after imposing $E_{RD} + E_I = E_T$. Finally, we factorize and solve for the derivative of interest.

$\frac{\partial E_{RD}}{\partial F} > \frac{\partial E_{RD}}{\partial px}$ and therefore $\frac{E_I}{F} > \frac{E_I(E_T\mu - px + r)}{px(E_T\mu + px + r)}$.

$\square$

However, governments may prefer to increase the fine rather than the expenditure associated with the sampling rate due to budget constraints. In general, as stated in the previous proposition proof, this alternative will be preferable for low levels of imitation.

The following proposition concerns the effect of changes in human capital endowments on the share allocated to R&D. The relationship has no obvious sign under the model assumptions. This is due to the fact that human capital can move into either innovation or imitation activities. Thus, the following proposition establishes the conditions under which a marginal increase in human capital endowment increases innovation.

Proposition 3. *An increase in total human capital, depending on the parameters, may or may not increase the share of human capital allocated to the R&D sector.*

Proof. The derivation of the proof is obtained by implicitly differentiating equation (9) with respect to E_T:

$\frac{\partial E_{RD}}{\partial E_T} = \frac{\Omega\mu + 2\mu px F r_M}{2\mu px F r_M}$

The numerator is composed of a positive and a negative term, hence the sign of this derivative is undefined, but there is an F that makes this derivative positive. That is, if there are no incentives for innovation, additional human capital moves into the imitation sector. The derivative of human capital in R&D with respect to total human capital and the fee F can be expressed as :

$\frac{\partial 2 E_{RD}}{\partial F \partial E_T} = \frac{\Pi^M(E_T\mu + px + r)^2}{2F^2 px(E_T\mu + r)^2} = \frac{2E_I}{F(E_T\mu + px + r)} + \frac{\Pi^M(E_T\mu + px + r)^2}{2F^2 px(E_T\mu + r)^2} > 0$

Furthermore, there is an F such that $\frac{\partial E_{RD}}{\partial E_T} = 0$, and for $F > \overline{F}$ the derivative with respect to human capital will be strictly positive. This threshold fine can be expressed as follows:

$\overline{F} = \frac{\Pi^M(E_T\mu + px + r)^3}{2px(E_T\mu + r)^2(2E_{RD}\mu - E_T\mu + px + r)}$

$\square$

Proposition 4. *The effect of human capital on R&D is increasing in px and F.*

Proof. The previous proposition stated that the derivative of human capital dedicated to R&D with respect to total human capital is increasing on F. This derivative is also increasing on px:

$\frac{\partial 2 E_{RD}}{\partial px \partial E_T} = 1/2\left(\frac{4E_I\mu(E_T\mu + r)}{(px(E_T\mu + px + r)^2)}\right) + \frac{\Pi^M}{F}\left(\frac{1}{px^2} - \frac{1}{(E_T\mu + r)^2)}\right) > 0$

$\square$

Since the level of human capital in R&D activities depends on institutions, and GDP depends positively on total human capital, we can derive the following corollaries about the nonlinear effects of human capital and IPRs on the R&D share in the GDP. The R&D share in GDP is defined as $\frac{RD}{Y} = \frac{wE_{RD}}{wE_T} \leqq 1$. The following corollary is obtained by differentiating this expression:

Corollary 2. *The share of R&D in GDP increases with the sampling probability, p, or with the government expenditure, x, or with the amount of the fine, F. These variables show decreasing marginal returns. These relationships are non-linear.*

Proof. The respective derivatives can be expressed as functions of the derivatives of human capital in R&D divided by total human capital, hence is straightforward to show that the impacts of F and px are positive:

$$\frac{\partial(RD/Y)}{\partial F} = \frac{1}{E_T}\frac{\partial E_{RD}}{\partial F} > 0$$
$$\frac{\partial(RD/Y)}{\partial px} = \frac{1}{E_T}\frac{\partial E_{RD}}{\partial px} > 0$$

The decreasing marginal returns are proved by noting that the following second derivatives are negative:

$$\frac{\partial^2(RD/Y)}{\partial F^2} = \frac{1}{E_T}\frac{\partial^2 E_{RD}}{\partial F^2} = \frac{1}{E_T}\left(-\frac{\partial E_{RD}}{\partial F} - \frac{E_I}{F^2}\right) < 0$$
$$\frac{\partial^2(RD/Y)}{\partial(px)^2} = \frac{1}{E_T}\frac{\partial E_{RD}^2}{\partial(px)^2} = \frac{1}{E_T}\frac{\partial}{\partial px}\left(\frac{E_I(E_T\mu - px + r)}{px(E_T\mu + px + r)}\right)$$
$$\frac{\partial^2(RD/Y)}{\partial(px)^2} = \frac{1}{E_T}\left(-\frac{\partial E_{RD}}{\partial px}\frac{(E_T\mu - px + r)}{px(E_T\mu + px + r)} + E_I\frac{(-1)px(E_T\mu + px + r) - (E_T\mu - px + r)2px}{(px(E_T\mu + px + r))^2}\right) < 0 \qquad \square$$

Corollary 3. *Depending on the parameters, the share of R&D in GDP may or may not increase with total human capital, and this relationship is non-linear.*

Proof. The respective derivatives can be expressed as functions of the derivatives of human capital in R&D divided by total human capital, hence it is straightforward to show that the effects of F and px on the incidence of R&D are positive:

$$\frac{\partial(RD/Y)}{\partial E_T} = \frac{1}{E_T}\frac{\partial E_{RD}}{\partial E_T} - \frac{1}{E_T}\frac{E_{RD}}{E_T} = \frac{E_T\left(2 - \frac{\Pi^M(E_T\mu + px + r)^2}{Fpx(E_T\mu + r)^2}\right) - \frac{2\left(2E_T^2\mu + \mathrm{Erd}(-E_T\mu + px + r)\right)}{E_T\mu + px + r}}{2E_T^2} \qquad (10)$$

$$\square$$

Corollary 4. *If $E\mu > px + r$ the cross derivatives of share of R&D in GDP with respect to total human capital and enforcement of IPRs, px, and F are positive.*

Proof. By differentiating the equation 10 with respect to px and F we obtain:

$$\frac{\partial^2(RD/Y)}{\partial F \partial E_T} = \frac{\Pi^M(E_T\mu + px + r)^2}{2\mathrm{Et}F^2px(E_T\mu + r)^2} + \frac{2E_I F(E_T\mu - px - r)}{2\mathrm{Et}^2F^2(E_T\mu + px + r)} > 0$$

$$\frac{\partial^2(RD/Y)}{\partial px \partial E_T} = \frac{E_I\left(E_T^2\mu^2 + px^2 - r^2\right)}{E_T^2px(E_T\mu + px + r)^2} + \frac{\Pi^M\left(\frac{1}{px^2} - \frac{1}{(E_T\mu + r)^2}\right)}{2\mathrm{Et}F} > 0$$

$$\square$$

Corollaries 1-4 suggest that under nonrestrictive assumptions there is non-separability of IPRs and human capital accumulation in the determination of the incidence of R&D. These relationships are also non-linear and the impact of IPRs protection is positive whereas the impact of human capital

is positive under particular conditions. Thus, in our empirical section we depart from traditional estimation of linear and separable functional form of the relationship between R&D, IPRs, and human capital.

3 Empirical Evidence

The theoretical model provides testable hypotheses. In brief, we expect that international differences in R&D as a share of GDP depend on human capital, intellectual property rights (including enforcement), and non-linear interactions between these variables. The econometric models (discussed below) that assess the validity of our theoretical predictions rely on data on R&D, educational attainment, and IPRs that are commonly used in empirical applications.

3.1 Data and identification

The historical R&D series from 1960-2000 were compiled by Lederman and Saenz (2005) from various sources, but the data are derived ultimately from national surveys that use a common definition of R&D expenditures that includes fundamental and applied research as well as experimental development.[4] The data thus include not only investments in labor and materials needed to conduct basic scientific research in advanced countries, but also corresponding investments in the adoption and adaptation of existing technologies often thought more germane to developing countries. The series were constructed from data published by UNESCO, the OECD, the Ibero American Science and Technology Indicators Network (RICYT) and the Taiwan Statistical Data Book. The Lederman and Saenz data were updated to the latest year available for 2000-2004 from the UNESCO web site. We work with five year averages of R&D as a share of GDP from 1960-2004.

The educational attainment data come from Barro and Lee (2001). More specifically, we use the variable on the average years of education of the adult population (25-64 years) as the proxy of total human capital. These data are available every five years, beginning in 1960, thus corresponding to the initial year of each five-year average of the R&D variable.

We use the aggregate Ginarte-Park IPR index (Ginarte and Park 1997), which is the simple average of five component indexes concerning each country's IPR laws in terms of its coverage and enforcement. The index's five components are the coverage of patent laws across seven industries, membership in three international agreements, loss of protection due to three potential reasons

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[4]See UNESCO Statistical Yearbook (1980) p. 742. The definition of R&D is the same across secondary sources, including the OECD, Ibero American Science and Technology Indicators Network (RICYT), World Bank, and Taiwan Statistical Yearbook. All these organizations follow the definitions provided by the Frascati Manual with the 2002 edition published by the OECD being its latest incarnation. For the purposes of this study, it is worth reproducing here the definition of experimental development, which is systematic work, drawing on existing knowledge gained from research and/or practical experience, which is directed to producing new materials, products or devices, to installing new processes, systems and services, or to improving substantially those already produced or installed (OECD 2002, p. 30).

(namely working requirements, compulsory licensing, and revocation of patents), three types of enforcement mechanisms, and the duration of patents relative to international standards.[5] Each component ranges between zero and one, and thus the composite index we use in the empirical exercises also varies between 0 and 1, with higher values indicating stronger IPR protections and enforcement. Summary descriptive statistics of the three variables and the list of 67 countries that appear in our sample are reported in the Appendix.

Finally, the data on IPRs are available in five year intervals, with the updated data from 1960-2000 available from Park's web site.[6] These data, like the educational attainment data, are thus also available for the initial year of each five-year period in our estimation sample. And both variables therefore can be treated as pre-determined or weakly exogenous with respect to the R&D variable in a temporal sense. Moreover, the educational attainment variable reflects educational enrollment decisions made roughly during ages 6-25, and therefore are unlikely to be due in a causal sense to the share of R&D observed in the subsequent 4 years. The IPR index is largely a summary indicator of the laws that establish the coverage and enforcement of IPR laws, which are the result of past international negotiations and legislative activity. Consequently it is difficult to believe that the index is caused by subsequent realizations of R&D.

3.2   Model specification

As mentioned, the theoretical model predicts that the relationship between R&D as a share of GDP and human capital and IPRs can be characterized by a non-linear function. Under the expectation of non-linear relationships, the ideal estimator would be a non-parametric estimator capable of estimating local derivatives over the data sample. Unfortunately, non-parametric estimators commonly used in empirical analyses tend to breakdown in the presence of multi-variate relationships and especially in the presence of fixed effects.[7] A more tractable alternative is to apply linear estimators to flexible functional forms using Taylor or Fourier approximations to non-linear functions of unknown form. The disadvantage of this general approach is the well known "curse of dimensionality," whereby the addition of higher-order polynomials or trigonometric terms in linear functions reduces the power of standard specification tests, such as the t-statistic, and thus we are unable to ascertain the statistical significance of each element in the high-order functions. On the other hand, we can apply standard F-tests to test the null hypothesis of insignificant higher-order and interactive terms in the chosen functions.[8] We apply three econometric approaches to assess the existence of

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[5]Regarding the enforcement mechanisms, the sub-index includes three de jure enforcement mechanisms: (a) Preliminary (pre-trial) injunctions, (b) Contributory infringement, and (c) Burden of proof reversal (see Ginarte and Park 1997, p. 287-88; and Park 2008).

[6]http://www.american.edu/cas/econ/faculty/park.htm

[7]See, for example, Stone (1980), White (1980) and Yatchew (2003).

[8]We thank Francisco Rodriguez of Wesleyan University for highlighting these econometric issues. See also his paper on growth empirics, Rodriguez (2007).

non-linearities among R&D, initial education, and initial de jure IPR.

3.2.1 Two-stage rolling regressions

The first approach entails a two-stage estimation procedure, which is purely descriptive. In the first stage, we estimate the semi-elasticity of R&D over GDP with respect to (the natural logarithm of) initial educational attainment, while controlling for country-specific fixed effects, over a moving window of observations ranked by the initial IPR index. In turn we estimate the correlation between the elasticities estimated in the first stage and each country's level of educational attainment and IPRs. Since the dependent variable in the second stage is not a precise statistic, but rather an estimated elasticity, the standard errors of the second-stage estimations are bootstrapped. Also, it is likely that the sample size of the window of observations can affect the estimated elasticities, and thus we report results from specifications with various window sizes.

More formally, the regression model to be estimated over each window of a subset of observations ranked by the level of IPRs is:

$$\left(\frac{RD}{GDP}\right)_{it} = \alpha + \beta \cdot \ln HK_{it-1} + \eta_i + \eta_t + \varepsilon_{it} \tag{11}$$

HK is human capital observed in the initial year of each five-year period, as reflected in its t-1 subscript, η_i is the country fixed effect, and η_t is time-period effect.

Figure 1 shows the estimated coefficients over the number of interactions corresponding to a rolling window of 60 observations.[9] This preliminary evidence shows that, in fact, the semi-elasticity of R&D over GDP with respect to educational attainment is generally positive, but it is clearly a non-linear function. The relationship between R&D and human capital is unstable and rising with the rank of the IPR index. Furthermore, the changes in the semi-elasticity seem to be discrete and unpredictable. It is zero in the samples with the worst levels of IPRs, then abruptly rises in the middle of sample, and stabilizes towards the end of the sample. These abrupt changes in the relevant semi-elasticity are not due to abrupt changes in the IPR index as we move up the rankings of IPRs. Considering that the each iteration involves a set of observations with increasing IPR index, the slope of the curve in Figure 1 corresponds approximately to the cross derivative of R&D share with respect to human capital and the IPR rank. Thus, we expect that this cross derivative could be positive on average for the whole sample. In any case, we discuss the results from our two-stage estimations further below.

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[9]We excluded one observation from the data, namely for El Salvador in 1980, as the Lederman and Saenz data had a value of 2.27% of GDP. This data point is consistent with the RICyT data, but it is impossibly high for a poor developing economy, and there were no data points within five years of this observation. Estimations with this observation also yielded notable unpredictable non-linearities. The corresponding graph is available from the authors upon request. We are grateful to Bill Maloney and Edwin Goni for pointing out this outlier.

3.2.2 Formal linearity and separability tests

As mentioned, we study non-linearities in the R&D function by estimating polynomial expansions of the linear function. The second order Taylor expansion is:

$$\left(\frac{RD}{GDP}\right)_{it} = \alpha_0 + \alpha_1 HK_{it-1} + \alpha_2 IPR_{it-1} + \alpha_3 HK_{it-1}^2 + \alpha_4 IPR_{it-1}^2 + \alpha_5 HK_{it-1} IPR_{it-1} \quad (12)$$

where subscripts i and t are countries and years. The null hypothesis that the function is linear is:

$$\alpha_3 = \alpha_4 = \alpha_5 = 0 \quad (13)$$

In other words, for the function to be linear, the quadratic and interactive terms in equation (11) need to be jointly zero. Equation (11) can be estimated with Ordinary Least Squares, and a traditional F-test for joint significance of the relevant parameters can be applied to ascertain whether the function is linear. In addition, the null hypothesis of the separability test concerns the cross derivative:

$$\alpha_5 = 0 \quad (14)$$

The third order Taylor expansion includes additional terms, namely the cubic of each explanatory variable and the interaction between the square of each explanatory variable and the other. Hence the test for linearity would entail the F-test for the joint significance as in (11) above, but with the additional terms included in the equality condition. Likewise, the separability test for the cubic expansion would include the coefficients on the additional interactive terms.

As a preliminary step to explore the differences across the linear, second order, third order functional forms, Figure 2 contains graphs of the resulting fitted functions. The graphs show the scatter plot of R&D over GDP as functions of the schooling variable. It is evident that the slope of the function depends on the value of schooling for all functional forms, except the linear function. Hence the discussion of the results includes an exploration of the average slope or effect of the explanatory variables on R&D over GDP for the global sample and for various regions (groups of countries) when appropriate.[10]

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[10]We also present econometric estimates that control for time dummies, which capture any period specific effects that are common to all countries, such as variations in global interest rates.

4 Results

We discuss the three sets of results separately, starting with the descriptive two-stage estimations with rolling windows of observations ranked by the IPR index variable. In turn, we discuss the results from the second order, third order, and Fourier functional forms, with special attention given to the tests of the null hypotheses of linearity and separability.

4.1 Suggestive evidence of non-linearities from two-stage estimations

Figure 1 shows the estimated quasi-elasticities linking R&D over GDP to the (log of) years of schooling of the adult population, based on the five-year averages panel data discussed earlier. Table 1 shows the results from the second-stage regressions, where the dependent variable is the vector of quasi-elasticities estimated with the various windows of observations. That is, we used windows of between 30 and 80 observations, as listed in the first row of the table. The level of schooling itself seems to be significantly correlated with the estimated quasi elasticities from the first stage estimation, thus suggesting that the effect of schooling is not linear. In addition, this suggestive evidence also seems to show that the level of the IPR index also tends to affect the quasi elasticities of R&D over GDP with respect to schooling, but these results are less robust across the window sizes. This type of sensitivity is expected, since we do not know what would be the optimal window size for this type of estimation. Nevertheless, there is sufficient evidence of non-linearities and perhaps of non-separability to turn our attention to the formal tests of linearity and separability.

4.2 Formal tests of linearity and separability based on second-order and third-order functional forms

Table 2 contains the results from random effects, fixed-effects, and time-effects specifications of the second order polynomial functional form. The table includes the coefficient estimates, the p-values of the null hypotheses of linearity and separability, as well as the Hausmann specification test for equality of the random- and fixed-effects estimations.

As expected, few coefficients are statistically different from zero. In this regard, it is actually surprising that the interactive term between schooling and the IPR index is highly significant across all specifications. Thus we can safely reject the null of separability. Moreover, the p-value of the corresponding F-test safely rejects the null of linearity. That is, we cannot reject the possibility that the squared terms in the model are jointly significant, although each one of them does not appear to be individually significant. The curse of dimensionality comes out loud and clear, even in the second-order functional form.

The lower panel of Table 2 shows the average derivatives for the global sample and for the geographic regions. As mentioned earlier, we cannot know the confidence interval around each

average derivative. But it is interesting to note that all derivatives are positive and seem to be consistently estimated across the various specifications. The High-Income countries tend to have the highest marginal effects of schooling on R&D effort as a share of GDP.

Table 3 presents the specification tests for the null of linearity and separability, as well as the test of equivalence of the random- and fixed-effects specifications of the third-order functional form. It also reports the average first derivatives of the R&D over GDP with respect to schooling, as well as the average cross derivatives (i.e., how the first derivative changes with marginal changes in the IPR index).

The results suggest, again, that we can safely reject the null of linearity. The test of separability is more mixed, with the fixed-effects specifications unable to reject separability. However, the Hausmann tests for equivalence between the random- and fixed-effects specifications suggest the more efficient random-effects estimation is preferable, as we cannot reject that the set of coefficients from the random- and fixed-effects estimations are statistically similar. Since the preferred random-effects specification rejects separability, we conclude that in the third-order polynomial function there is evidence that the underlying function is both non-linear with potentially important interactions between IPRs and schooling. In this regard, the estimates of the average cross-derivatives suggest that the marginal effects of schooling on R&D expenditures as a share of GDP is positively affected by the level of IPR protection as the model predicts. This result appears for all regions of the world, but the point estimates tend to be larger for developing countries than for the High-Income countries.

As a robustness check we estimated various Fourier trigonometric expansions of the R&D function. These results, which are available upon request, also rejected the null of separability of human capital and IPRs.[11]

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[11]The Fourier expansion implemented is the Taylor second order expansion but with additional trigonometric terms. The advantage of this specification is that the resulting functions are more flexible. More formally, following Yatchew (2003), the Fourier expansion can be written as:

$$\left(\frac{RD}{GDP} \right)_{ij} = \alpha X + \sum_{i=1}^{k} b_i z_i + \sum_{i=1}^{3} \sum_{j=1}^{3} c_{ij} z_i z_j + \sum_{i=1}^{3} \left\{ \mu_{ij} \cos(jk_i' z) + \nu_{ij} sin(jk_i' z) \right\} \tag{15}$$

where the linear part of the equation is $\alpha \cdot X$. The z's are our two explanatory variables. The second and third terms in (14) are the terms from the second order expansion. The k's are vectors whose elements are integers with absolute values summing to a number k less than a pre-specified value K*. Given a value of K* and J, the parameter vector can be estimated by OLS. The choices of K* and J are somewhat arbitrary. In our case, K*=3. The total number of terms in the expansion is supposed to grow with sample size. In practice, researchers look at the ratio of the total number of parameters in the expansion to the number of observations. We can obtain a restricted estimator by restricting the coefficients on the terms involving interactions between different z variables to equal zero. Thus, the separability test for the Fourier expansion is the test used for the second order expansion but including the trigonometric parameters in the set to be tested for joint significance. There is not linearity test specific to the Fourier expansion. In any case, the point is that the trigonometric terms add flexibility to the function, but also add complexity. Tests for the cases of K=2, K=3, J=1 and J=2 rejected the null of separability at less than the 5% confidence level.

5 Concluding Remarks

We extended the model by Aghion and Howitt (1992) to take into account the role of intellectual-property institutions in the process of innovation. Our model consists of two sectors that operate simultaneously, one relying on costly imitation and the other on innovation. Firms or entrepreneurs decide endogenously whether to participate in innovative or imitative activities. The enforcement of intellectual property rights affects the incentives of labor to move between the two sectors. That is, institutions determine the risk-adjusted relative discount rate between employment in the two sectors. A second theoretical result is that an increase in the endowment of human capital increases the share of labor devoted to R&D activities under strong protection of IPRs.

Perhaps more importantly, the model predicts that aggregate patterns of the R&D shares across countries depend on complex interactions between IPRs and human capital. In spite of these complex interactions, the model also predicts, under fairly nonrestrictive assumptions, that IPRs provide incentives for the allocation of human capital into R&D activities. Economies with lax IPRs may not experience increases in the incidence of R&D over GDP as a result of increases in the stock of human capital. The model suggests that a minimum level of protection of IPRs can ensure that human capital accumulation increases the share of R&D. Thus, the model yields a testable prediction, namely that the share of R&D in GDP is a non-linear function of IPRs and human capital. While existing theories predict differential effects of IPRs on poor versus rich countries, the existing empirical literature has focused exclusively on log-linear functions of R&D determinants (e.g., Varsakelis 2001; Chen and Puttitanum 2005). The analyses here thus contributed to both micro-founded theory and evidence by highlighting an ignored aspect of the role of IPRs as institutions shaping incentives for human capital to be allocated to R&D within countries.

The empirical section of the paper focused on international data on R&D shares of GDP, years of schooling of the adult population, and the Ginarte and Park (1997) data on de jure intellectual property rights. The data on educational attainment and IPRs were safely treated as being pre-determined. Preliminary and descriptive estimations of the quasi-elasticity of R&D over GDP as a function of schooling suggested that in fact the data do seem to behave as if the underlying data generation process were unpredictably non-linear, and highlighting a new stylized fact: at low levels of IPRs, marginal increases in the stock of education have negligible effects on R&D.

We estimated basic models of the determinants of R&D expenditures as a share of GDP to test for non-linearities and interactions between the schooling of the labor force and the quality and enforcement of intellectual property rights, while also controlling for unobserved international heterogeneity with country specific effects. Non-parametric estimators cannot estimate such functions, and thus the applied literature has focused on polynomial and trigonometric approximations to non-linear functional forms.

The estimation of second-order, third-order and Fourier polynomial functions allowed us to test the validity of the null of linearity and separability in the R&D functions. The preponderance of the evidence suggests that we can reject linearity and separability, thus lending credence to the theoretical model. Moreover, the point estimates we obtain confirm the positive marginal effects of human capital and IPRs on R&D as well as the significance of their interactions. It is noteworthy that the effect of education on R&D effort can depend on intellectual property rights across countries of diverse levels of development, even after controlling for time-invariant heterogeneity.

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Appendix

Descriptive Statistics

Variable	Observations	Mean	Std. Dev.	Min.	Max.
R&D/GDP (%)	228	1.091	0.915	0.001	4.399
Average Years of Schooling	228	6.502	2.716	0.308	12.247
IPR Index	228	2.742	0.910	0.330	4.857

List of Countries with Regional Identifiers

1. ARGENTINA LAC 2. AUSTRALIA HI 3. AUSTRIA HI 4. BELGIUM HI 5. BOLIVIA LAC 6. BRAZIL LAC 7. CAMEROON SHA 8. CANADA HI 9. CHILE LAC 10. CHINA P.REP. EAP 11. COLOMBIA LAC 12. COSTA RICA LAC 13. CYPRUS MENA 14. DENMARK HI 15. ECUADOR LAC 16. EGYPT MENA 17. EL SALVADOR LAC 18. FINLAND HI 19. FRANCE HI 20. GERMANY HI 21. GHANA SHA 22. GREECE HI 23. GUATEMALA LAC 24. GUYANA LAC 25. HONDURAS LAC 26. HONG KONG EAP 27. HUNGARY ECA 28. INDIA SA 29. INDONESIA EAP 30. IRAN MENA 31. IRELAND HI 32. ISRAEL MENA 33. ITALY HI 34. JAMAICA LAC 35. JAPAN HI 36. JORDAN MENA 37. KENYA SHA 38. MALAWI SHA 39. MAURITIUS SHA 40. MEXICO LAC 41. NETHERLANDS HI 42. NEW ZEALAND HI 43. NORWAY HI 44. PAKISTAN SA 45. PANAMA LAC 46. PERU LAC 47. PHILIPPINES EAP 48. PORTUGAL HI 49. SENEGAL SHA 50. SINGAPORE EAP 51. SOUTH AFRICA SHA 52. SOUTH KOREA EAP 53. SPAIN HI 54. SRI LANKA SA 55. SUDAN SHA 56. SWEDEN HI 57. SWITZERLAND HI 58. THAILAND EAP 59. TRINIDAD/TOBAGO LAC 60. TUNISIA MENA 61. TURKEY ECA 62. UGANDA SHA 63. UNITED KINGDOM HI 64. UNITED STATES HI 65. URUGUAY LAC 66. VENEZUELA LAC 67. ZAMBIA SHA

Table 1: Second Stage Regression Estimates of the Determinants of the R&D/GDP Quasi-Elasticity with Respect to Schooling across Sample-Window Sizes

	Sample-Window Size					
	30	**40**	**50**	**60**	**70**	**80**
Average Years of Schooling	0.134	0.032	0.051	0.092	0.114	0.111
	[0.000]***	[0.278]	[0.000]***	[0.000]***	[0.000]***	[0.000]***
Intellectual Property Rights Index	0.064	0.289	0.18	0.059	-0.002	0.015
	[0.492]	[0.000]***	[0.000]***	[0.001]***	[0.926]	[0.411]
Obs.	165	155	145	135	125	115
R-Squared	0.449	0.71	0.821	0.872	0.933	0.959

Notes: Fixed Effects were included in the First Stage. Variables were calculated as the country mean for each window. The original units are 5-year averages of the R&D/GDP variable, and the value of the schooling and IPR index variables in the initial year of each 5-year period. The data cover the period from 1960-2004, but the panel is unbalanced. P-values from bootstrapped standard errors for the null appear within brackets; $*p < 0.1, **p < 0.05, ***p < 0.01$.

Table 2: Regression Results for the Second-Order Polynomial Function

	No FE	FE	RE	FE&TE	RE&TE
Average Years of Schooling (H)	-0.147	-0.143	-0.151	-0.195	-0.152
	[0.060]*	[0.144]	[0.039]**	[0.105]	[0.045]**
Intellectual Property Rights (IPR) Index	0.095	0.064	0.153	0.079	0.156
	[0.671]	[0.856]	[0.514]	[0.825]	[0.512]
Schooling Squared	-0.003	0.010	0.008	0.013	0.008
	[0.663]	[0.154]	[0.162]	[0.102]	[0.184]
IPR Squared	-0.111	-0.085	-0.101	-0.073	-0.090
	[0.056]*	[0.175]	[0.051]*	[0.258]	[0.088]*
Schooling*IPR	0.127	0.074	0.086	0.064	0.080
	[0.000]***	[0.020]**	[0.002]***	[0.053]*	[0.005]***
Obs	228	228	228	228	228
R-Squared	0.555	0.380		0.406	
R-Squared: Overall		0.519	0.538	0.518	0.549
Linearity Test: P-Value	0.000	0.001	0.000	0.003	0.000
Separability Test: P-Value	0.000	0.020	0.002	0.053	0.005
FE=RE: P-Value			0.023		0.997
First Derivative by Region:			$\frac{\partial}{\partial H}\left(\frac{R\&D}{GDP}\right)$		
World Sample	0.165	0.198	0.189	0.145	0.171
East Asia and the Pacific	0.117	0.152	0.142	0.100	0.126
Europe and Central Asia	0.085	0.089	0.085	0.034	0.071
High-Income Countries	0.232	0.281	0.270	0.230	0.248
Latin America/Caribbean	0.075	0.115	0.104	0.065	0.090
Middle East/N. Africa	0.155	0.173	0.167	0.118	0.150
South Asia	0.084	0.066	0.065	0.007	0.052
Sub-Saharan Africa	0.202	0.114	0.128	0.042	0.110

Notes: P-values for the null appear within brackets; $*p < 0.1, **p < 0.05, ***p < 0.01$.
FE=Fixed Effects; RE=Random Effects; TE=Time Effects. The Regional groups are those of the World Bank. Derivatives are calculated at regional means.

Table 3: Regression Results for the Third-Order Polynomial Function

Specification Test	No FE	FE	RE	FE&TE	RE&TE
Linearity Test: P-Value	0.000	0.007	0.000	0.007	0.000
Separability Test: P-Value	0.000	0.261	0.016	0.315	0.014
FE=RE: P-Value			0.348	0.991	
Obs	228	228	228	228	228

Implied First Derivative by Region:			$\frac{\partial}{\partial H}\left(\frac{R\&D}{GDP}\right)$		
World Sample	0.230	0.247	0.231	0.172	0.201
East Asia and the Pacific	0.170	0.192	0.179	0.117	0.149
Europe and Central Asia	0.062	0.070	0.069	-0.012	0.035
High-Income Countries	0.253	0.302	0.280	0.225	0.241
Latin America/Caribbean	0.106	0.138	0.127	0.064	0.097
Middle East/N. Africa	0.213	0.215	0.204	0.139	0.174
South Asia	-0.001	0.000	0.008	-0.083	-0.025
Sub-Saharan Africa	0.106	0.049	0.082	0.014	0.089

Implied Cross Derivative by Region:			$\frac{\partial}{\partial H \partial IPR}\left(\frac{R\&D}{GDP}\right)$		
World Sample	0.133	0.073	0.081	0.063	0.071
East Asia and the Pacific	0.148	0.084	0.091	0.074	0.086
Europe and Central Asia	0.176	0.109	0.118	0.119	0.132
High-Income Countries	0.101	0.046	0.054	0.024	0.028
Latin America/Caribbean	0.160	0.093	0.097	0.081	0.096
Middle East/N. Africa	0.144	0.083	0.092	0.082	0.091
South Asia	0.188	0.122	0.132	0.145	0.157
Sub-Saharan Africa	0.184	0.127	0.148	0.189	0.192

Note: Derivatives are calculated at the regional means of the relevant variables.

Figure 1. The Marginal-Effects Coefficient of log(Human Capital) Depends on the Ranking of Observations in Terms of Intellectual Property Protection

Human Capital Coefficient: Rolling Regressions with Fixed Effects
Observations ranked by IP

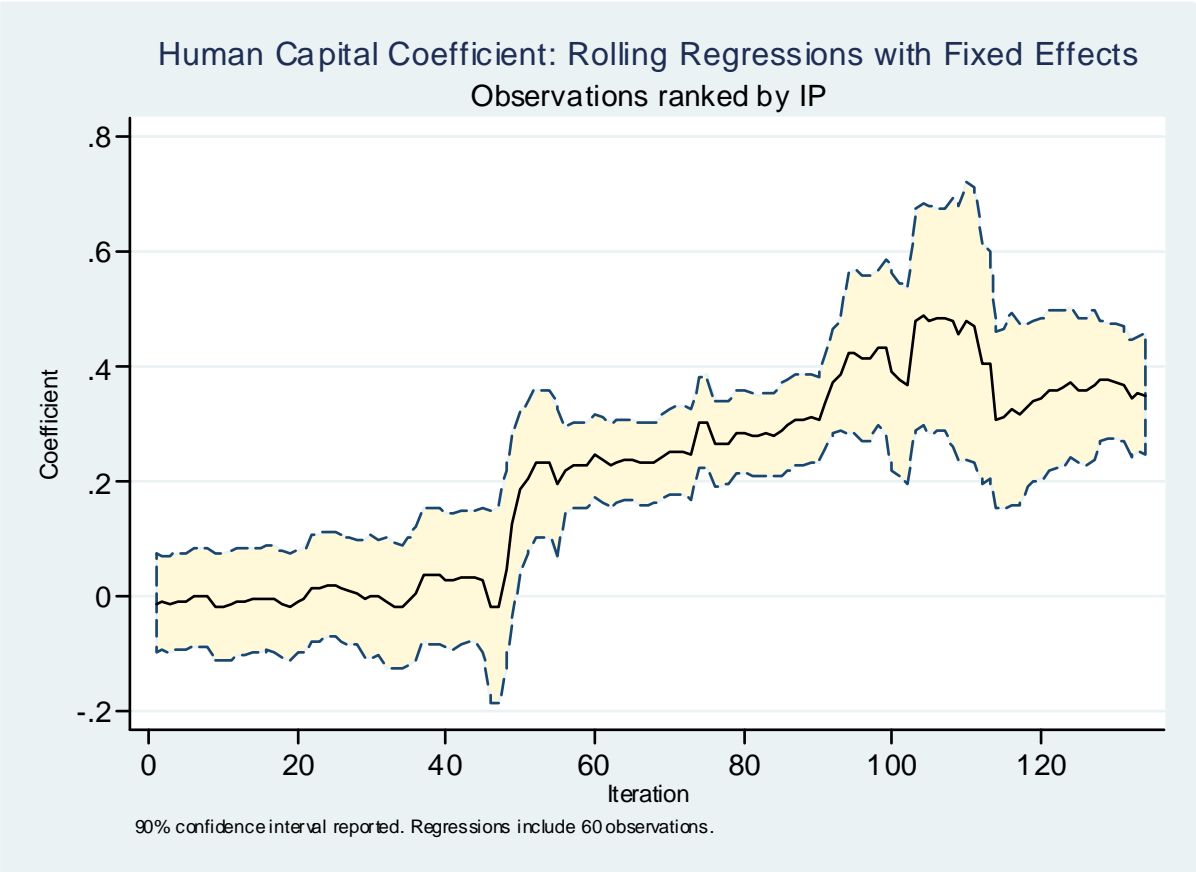90% confidence interval reported. Regressions include 60 observations.

Figure 2. R&D over GDP versus Years of Education across Functional Forms