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

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September 15, 2008
Preliminary Version– Comments Welcome

Abstract

The authors extend the model by Aghion and Howitt (1992) to highlight the role of intellectual-property-rights (IPRs) in the process of innovation and structural change. Consistent with previous theories, the model predicts, that reductions in the risk-free discount rate increases firm's and aggregate research and development (R&D) expenditures . The model suggests that the enforcement of IPRs has positive effects on the of R&D. It also predicts that human capital fosters R&D activities. At the aggregate level, the model predicts that national R&D expenditures as a share of GDP will depend not only positively on the level of human capital and intellectual property rights, but that there are interactions between these two variables, and their effects on R&D might follow unknown functional forms. The preponderance of the empirical evidence suggests that complex interactions between human capital and IPRs determine global patterns of R&D effort.

Keywords: R&D, Intellectual Property Rights, Development, Institutions.

JEL Classification: O11, O31, O34 .

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[*] We thank Javier Cravino and Valentina Paredes for stellar research assistance. We had helpful discussions with Francisco Rodriguez about non-linear functional forms in econometrics. We thank Bill Maloney, Edwin Goni and Jose Miguel Benavente for helpful discussions about R&D models and data. We gratefully acknowledge financial support from Fondecyt Grant 1061137 and from the World Bank's Latin America and the Caribbean Regional Studies Program. The usual disclaimer applies and all remaining errors are ours.

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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. The literature on Intellectual Property Rights (IPRs) and innovation can be viewed as a sub-field of this general area. 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 complex 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 our model.

One longstanding strand of the literature that relates 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 policymaker'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, Llobet and Mitchell (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 possibility of costly imitation in the design of the optimal patent length. However, in this framework there is no imitation when the patent length is optimal. This situation is likely to be created by the uniformity of patents lengths within a class of patents that is supposed to fit all innovations, when indeed 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 by choosing investment in R&D and in a spillover-absortive capacity coefficient, under a Cournot setting. Nevertheless, institutions play no role in shaping investment decisions. In our model we depart from previous literature by taking the patent length as given and allowing simultaneusly costly imitation and innovation. In addition we model the role of IPR enforcement in determining the incentives of firms to choose innovative activities over 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 counterintuitive results. For example, relaxing IPRs in the South might bring benefits to the innovating developed economies. Similarly, spillovers might make the strengthening of IPRs in the South benefitial for the welfare of developing economies, as more 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 assumed away. 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 (2004) extend traditional models by considering a two-country setup with costless imitation, enforcement and national treatment of patents. They study optimal patent policies for countries engaged in trade. However, the enforcement of patents is modeled as a probability in instantaneous monopolistic profits, neither controlling for changes in risk, nor modeling the process of enforcement and punishment through monitoring and fines. Branstetter et al (2005) develop a model of intellectual property rights, imitation and FDI. In their model Northern firms innovate, and, as usual, Southern just imitate.

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 simultaneusly with costly imitation and innovation, where workers decide endogenoulsy whether to participate in innovative or imitative activities. 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 between employment in the two sectors and the stream of profits. This discount rate affects the present value of marginal productivity of labor, which are also affected by the fees and compensations derived from the enforcement of the IPRs. A second result is that an increase in the endowment of human capital increases the share of labor devoted to R&D activities. This result comes from differences in the human-capital intensity of the technology used in each sector. Perhaps more importantly, the model predicts that aggregate R&D shares will depend on complex interactions between the quality and enforcement of IPRs and human capital endowments. Hence, countries with low levels of human capital but with strong IPRs can have high rates of R&D.

Thus, the model yields a testable prediction, namely that the share of R&D expenditures in GDP is a non-linear function of IPRs and human capital. The existing empirical literature, however, has focused exclusively on log-linear functions of R&D determinants (e.g., Varsakelis 2001). We provide empirical tests of functional linearity and separability of human capital and IPRs in an R&D model. The preponderance of the evidence seems to support 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 tradeoff between R&D and illegal imitation activities. There is just one input, human capital, which is allocated between these two activities.

As in Aghion and Howitt (1992), we assume that innovation follows a poisson process with parameter λ and exhibits constant returns to scale in the human capital occupied in R&D. Illegal imitation follows a poisson process of 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. The success rate in reverse engineering is greater than the one in the R&D sector. One crucial diference between the two sectors is that the innovation sector must incur a fixed cost of infrastrucutre of magnitude K.[1]

We assume that there is a patent enforcement effort exerted by the government, and that patents are infinitely lived for the sake of clarity of exposition.[2] We assume that the enforcement process follows a poisson distribution of parameter p, in which p represents the sampling probability for any given imitating firm. There is also constant returns to scale in government expenditure, x, which increases the efficiency of the enforcement process. The

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[1] We are aware that imitations entail significant costs in infrastructure, but they tend to be smaller in relative terms than the cost of innovation. See, for example, Mansfield et.al. (1981).

[2] We restrict our analysis to the case of an infinitely lived patent, however our results hold for the case of finitely lived patents. See footnote 4.

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 tranferred 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 the 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 the similarities in cost structures among them.

We further assume that a firm that has a monopolistic position 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 equals r.

2.1 Labor Market

In equilibrium, the wage paid by each firm corresponds to the marginal product of human capital. Let V represent the value of an invention. The wage paid in the innovation ($R\&D$) sector 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 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 stands for the value of an illegal imitation.

In equilibrium wages should be 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, E_T stand for the human capital employed in the R&D sector, imitating sector and total amount respectively.

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:

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

The respective poisson processes are parametarized with those rates. The present value of profits for firms in the R&D sector are:

$$V = \int_0^\infty e^{-rt} \pi^M e^{-\lambda E_{RD} t} e^{-\mu E_I t} dt + \int_0^\infty \mu E_I e^{-\mu E_I t} \int_t^\infty e^{-rv} \pi^D e^{-\lambda E_{RD} v} e^{-\mu E_I (v-t)} e^{-px(v-t)} dv dt + EPV(F) - K \tag{5}$$

The first term in (5) establishes that the discounted flow of monopolistic profits will stop with a new innovation or imitation. The second term concerns duopolistic profits, but this flow is conditional on the existence of a previous imitation and the absence of enforcement. The third and fourth terms in (5) correspond to the expected value of the fine or transfer minus the fixed cost, K. The solution of the previous integrals is:

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

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 F. Thus, the discounted flow of profits can be expressed as follows:

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

Solving the previous integrals we obtain the following expression:

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

which 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 for illegal imitation. From equation (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 are equalized across sectors equilibrium. Considering that the expected wages depend on the expected value of inventions and imitating, the wage equalization condition can be written as follows:

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

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}, E_I.[3]

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[3] 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 $V' = V \cdot \left(1 + \frac{1}{r(T^*)} + \frac{1}{r(T^*)^2} + \frac{1}{r(T^*)^3} \ldots\right)$. The same wil happen with $I' = I \cdot \left(1 + \frac{1}{r(T^*)} + \frac{1}{r(T^*)^2} + \frac{1}{r(T^*)^3} \ldots\right)$. Once the innovation and imitation values are equalized, the factors associated with the repetitions of the sequence will cancel each other out.

2.4 Comparative Statics

Before continuing with the comparative statics exercise, we present necessary assumptions about model parameters:[4]

Assumption 1 *Define:*
$\Phi(E_I) = \frac{\Pi^M}{r+\lambda\cdot(E_T-E_I)+\mu\cdot E_I} + 2\frac{F\cdot\mu\cdot E_I\cdot px}{(r+\lambda\cdot(E_T-E_I)+\mu\cdot E_I+px)^2}$
and
$\Lambda(E_I) = \frac{\Pi^M}{r+\lambda\cdot(E_T-E_I)+\mu\cdot E_I+px} + \frac{F\cdot\mu\cdot px\cdot(r+\lambda\cdot(E_T-E_I)+\mu\cdot E_I)}{(\mu-\lambda)(r+\lambda\cdot(E_T-E_I)+\mu\cdot E_I+px)^2}$
We assume that the model's parameters are such that:

$$Min\left(\Phi(E_T),\Lambda(E_T)\right) > K > \Phi(0) \text{ (a)}$$

Condition (a) is a sufficient condition for the existence of a single equilibrium with two sectors in which we are focusing, and will be used in our comparative statics exercise.

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.*

Proof: By implicitly differentiating equation (9) we obtain:
$\frac{\partial E_{RD}}{\partial r} = \frac{\Omega}{2\mu px F r_M - \Omega(\lambda-\mu)}$
with $\Omega = 2\Pi^M r_F + 2\mu px F(E_T - E_{RD}) - K(2r_F r_M + r_F^2)$
$r_M = r + \lambda E_{RD} + \mu E_I$
$r_F = r_M + px,$

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 $\Omega < 0$. However Assumption 1 guarantees that $2\mu px F r_M - \Omega(\lambda - \mu) > 0$, therefore $\frac{\partial E_{RD}}{\partial r} > 0$. ■

The previous proposition is consistent with existing literature that highlights the advantages of having a low interest rate, which will increase 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.

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[4]

with T being length of the patent.

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 derivation of the proofs is obtained by implicitly differentiating equation (9).

$\frac{\partial E_{RD}}{\partial F} = \frac{2\mu px E_I r_M}{2\mu px F r_M - \Omega(\lambda-\mu)}$

Given that Assumption 1 ensures a positive denominator, $\frac{\partial E_{RD}}{\partial F} > 0$.

By the same token $\frac{\partial E_{RD}}{\partial px} = \frac{2\Pi_M r_F + 2F\mu E_I r_M - 2K r_F r_M}{2\mu px F r_M - \Omega(\lambda-\mu)}$, using the equilibrium condition it can be shown that the numerator is positive, thus $\frac{\partial E_{RD}}{\partial px} > 0$. ■

Corollary 1 *Depending on the parameters, it can be optimal to increase the effective sampling rate (px) or the fine in order to increase the level of R&D. If there is a "low" level of imitation, the best strategy to increase innovation is to increase the effective sampling rate. If there is a "high"level of imitation, the best strategy to increase innovation depends on the relationship between the effective sampling rate and the fine. Indeed, if the fine is greater than the effective sampling rate, the best strategy is to increase the effective sampling rate. On the other hand, if there is a high level of imitation, and the effective sampling rate is greater than the fine, then the best strategy to raise innovation is to increase the fine.*

Proof: The results are derived from the following inequalities and assumption 1:

$\frac{\partial E_{RD}}{\partial F} > \frac{\partial E_{RD}}{\partial px}$

$\frac{2\mu px E_I r_M}{2\mu px F r_M - \Omega(\lambda-\mu)} > \frac{2\Pi_M r_F + 2F\mu E_I r_M - 2K r_F r_M}{2\mu px F r_M - \Omega(\lambda-\mu)}$

$$\mu E_I r_M \cdot (px - F) > (\Pi_M - K r_M) \cdot r_F$$

■

As in Becker (1968), there is no obvious optimal decision between an increase in the sampling probability or in the fine. In Becker's case the optimal decision depends on the individuals preferences. However, from the budgeting point of view, governments, in general will find it preferable to increase the fine rather than the expenditure associated with the sampling rate.

The following proposition relates to the effect of a larger human capital endowment and the level of R&D. Although intuitive, this relationship has no obvious solution under the model assumptions. This is due to the fact that human capital can move either to innovation or imitation activities. Thus, this results needs to be proven in the following proposition.

Proposition 3 *An increase in the total human capital increases the share of human capital allocated to the R&D sector.*

Proof: The derivation of the proofs is obtained by implicitly differentiating equation (9) :

$\frac{\partial E_{RD}}{\partial E_T} = \frac{\Omega\mu + 2\mu px F r_M}{2\mu px F r_M - \Omega(\lambda - \mu)} = \frac{1}{\frac{2\mu px F r_M + \Omega\mu - \Omega\lambda}{2\mu px F r_M + \Omega\mu}}$

Thus, we obtain in the denominator a positive number, that is the result of the sum of one plus a number smaller than one, and that it is function of Ω. Therefore $\frac{\partial E_{RD}}{\partial E_T} > 0$ ■

Now we can analyze the impact of variable X on the share of R&D in GDP. Express the derivative of this ratio as folllows.

$$\frac{\partial}{\partial X}\left(\frac{R\&D}{GDP}\right) = \frac{\partial}{\partial X}(\frac{wE_{RD}}{wE_T}) = \frac{E_T \frac{\partial}{\partial X}(E_{RD}) - E_{RD}\frac{\partial}{\partial X}(E_T)}{E_T^2}$$

From the fact that the level of human capital in R&D depends on institutions, and the fact that total GDP depends positively on total human capital we can derive the following corollaries whose proof is straightforward.

Corollary 2 *The share of R&D in the GDP increases with the total human capital and this relationship is non-linear.*

Corollary 3 *The share of R&D in the GDP increases with the sampling probability, p, or with the government expenditure, x, or with the amount of the fine, F. These relationships are non-linear.*

Corollary 4 *The cross derivative of R&D with respect to total human capital and enforcement cannot be signed.*

The last corollary is important, because under very general assumptions the complementarity or sustitutability of enforcement and human capital, or more generally between institutions and human capital can not be established. This leaves this question theoreticaly unanswered, which gives further relevance to our empirical work. These results imply a departure from traditional estimations 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

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. [5] The data thus include not only the basic science expected in advanced countries, but also investments in the adoption and adaptation of existing technologies often thought more germane to developing countries. The series were constructed based on underlying 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.

Finally, the data on IPRs are available in five-year increments from Ginarte and Park (1997), with the updated data from 1960-2000 available from Park's web site. [6] We use the aggregate index, 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 (namely working requirements, compulsory licensing, and revocation of patents), three types of enforcement mechanisms, and the duration of patents relative to international standards. Each component ranges between zero and one, and thus the composite index we use in the empirical exercises also

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[5] 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).

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

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.

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 of unknown form. 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, the non-parametric estimators that are 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 non-linearities among the R&D, education, and IPR variables.

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) educational attainment, while controlling for country-specific fixed effects, over a moving window of observations ranked by the 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 obser-

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

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

vations 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:

$$\left(\frac{RD}{GDP}\right)_{it} = \alpha + \beta \cdot \ln HK_{it} + \eta_i + \varepsilon_{it} \tag{10}$$

, where HK is total human capital and η_i is the country fixed effect. Figure 1 shows the estimated coefficients over the number of interations 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-elasiticity 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.

3.2.2 Formal linearity and separabiliaty 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:

$$\left(\frac{RD}{GDP}\right)_{it} = \alpha_0 + \alpha_1 HK_{it} + \alpha_2 IPR_{it} + \alpha_3 HK_{it}^2 + \alpha_4 IPR_{it}^2 + \alpha_5 HK_{it} IPR_{it} \tag{11}$$

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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.

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

$$\alpha_3 = \alpha_4 = \alpha_5 = 0 \tag{12}$$

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:

$$\alpha_5 = 0 \tag{13}$$

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.

The Fourier expansion to be 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:

$$\left(\frac{RD}{GDP}\right)_{ij} = \alpha X + \sum_{i=1}^{k} b_i z_i + \sum_{i=1}^{3}\sum_{j=1}^{3} c_{ij} z_i z_j + \sum_{i=1}^{3} \{\mu_{ij} \cos(jk_i' z) + \nu_{ij} sin(jk_i' z)\} \tag{14}$$

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. Figure 2 shows, as illustrations, the estimated relationships between R&D over GDP as a function of educational attainment using the Taylor second and third order expansions for this bi-variate function, as well as the Fourier expansion.

As a preliminary step to explore the differences across the linear, second order, third order, and Fourier 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 clear that the most flexible functional forms come from the Fourier functions, but the assumptions regarding the values of J have notable effects on the predicted values. This reinforces the need to conduct sensitivity tests by estimating empirical models with various values of J. Furthermore, it is also 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]

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.

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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 risk free global interest rates.

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, third-order, and Fourier 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. 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.

Finally, Table 4 presents the separability tests for the Fourier trigonometric expansion of the second-order function, for various values of K and J. In all specifications, we can safely reject the null of separability, thus further strengthening the conclusions derived from the second-order and third-order polynomial functions. Hence the preponderance of the evidence clearly supports the main conclusions of our theoretical model, namely that the effects of human capital accumulation on R&D expenditures measured at the national (aggregate level) depend on the quality and enforcement of intellectual property rights.

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. Workers decide endogenoulsy 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 affect 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. This result comes from differences in the human-capital intensity of the technology used in each sector. Perhaps more importantly, the model predicts that aggregate patterns of the R&D shares will depend on complex interactions between the IPRs and human capital. Consequently, countries with low levels of human capital but with well enforced intellectual property rights can have high rates of R&D, and conversely, rich countries with poor IPRs can be specialized in imitation. 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. The existing empirical literature, however, has focused exclusively on log-linear functions of R&D determinants (e.g., Varsakelis 2001).

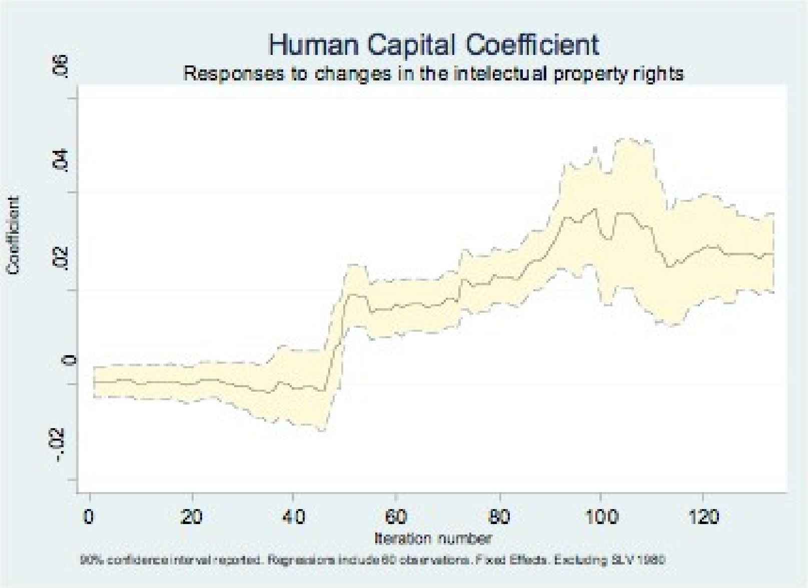
The empirical section of the paper focused on international data on R&D shares of GDP, years of schooling of the adult population, and the Ginarte and Park (1997) data on intellectual property rights. Preliminary and descriptive estimations of the quasi-elasticity of R&D over GDP as a function of schooling suggested that in fact the data does seem to behave as if the underlying data generation process were non-linear and according to unpredictable functional forms.

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 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 for 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. It is also noteworthy that the effect of education on R&D effort can depend on intellectual property rights across countries of diverse levels of development, after controlling for time-invariant heterogeneity.

6 Appendix.

Figure 1: The Marginal-Effects Coefficient of log(Human Capital) Seems to Depend on the Ranking of Countries in Terms of Intellectual Property Protection



Human Capital Coefficient

Responses to changes in the intelectual property rights

90% confidence interval reported. Regressions include 60 observations. Fixed Effects. Excluding SLV 1980

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

	Sample-Window Size					
	30	**40**	**50**	**60**	**70**	**80**
Average number of Schooling Years	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; $*p < 0.1, **p < 0.05, ***p < 0.01$.

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

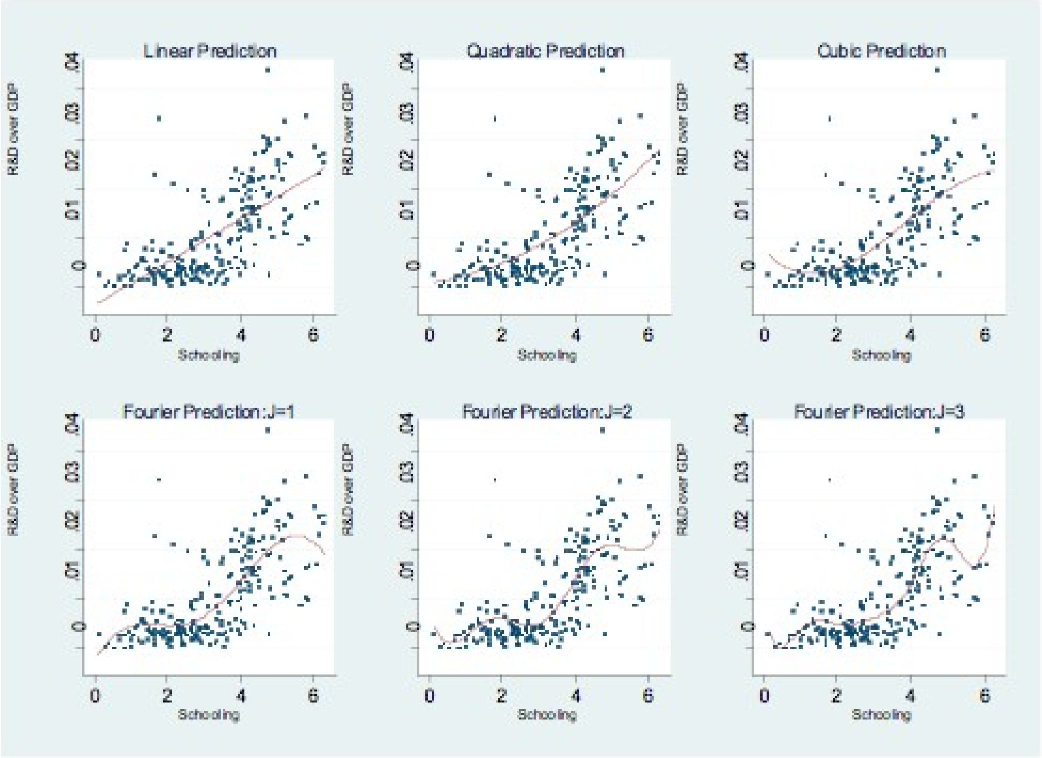


Table 2: Regression Results for the Second-Order Polynomial Function

	NoFE	FE	RE	FE&TE	RE&TE
Average Number Schooling Years (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 Thrid-Order Polynomial Function

Specification Test	NoFE	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 region means of the relevant variables.

Table 4: Separability Test Results from the Fourier Expansion

	K=2,J=1	K=2,J=2	K=3,J=1	K=3,J=2
Obs.	228	228	228	228
M	14	22	22	38
F-Test	1.797	4.367	3.425	5.787
p-value	0.036	0	0	0

Note: M includes the constant.

Table 5: Descriptive Statistics

Variable	**Obs**	**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	0.91	0.33	4.857

Table 6: List of Countries and Regions in the Sample Used for Regression Analyses

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