Upstream Innovation Protection: Common Law Evolution and the Dynamics of Wage Inequality

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Abstract

What is the most innovation-enhancing level of patent protection for the new ideas generated within the framework of multi-stage sequential innovation? How does increasing early innovation appropriability affect basic research, applied research, education, and wage inequality? What does the common law system imply on the macroeconomic responses to institutional change? We show how the jurisprudential changes in intellectual property rights witnessed in the US after 1980 can be related to the well-known increase in wage inequality and in education attainments. A Schumpeterian general equilibrium approach is followed. *Keywords*: Basic and Applied R&D, Sequential Innovation, Skill Premium, Inequality and Education, Research Exemption, Common Law. *JEL Classification*: O31, O33, O34.

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1 Introduction

As is well known, the US economy in the 1980s witnessed the following phenomena:

1. A sustained increase in the skill premium;
2. A sustained increase in the educated fraction of the population;
3. A strengthening of the intellectual property of upstream research[1].

Points 1 and 2 are well known[2] in the macroeconomics debate (see Acemoglu 2002 for an excellent review) and have motivated explanations based on directed change[3], globalization[4], government procurement[5]. In this paper, we assess the potential marginal importance of point 3.

In the recent US history[6] the patent system registered an explosion of upstream patents[7] (Heller and Eisemberg, 1998; Jensen and Thursby, 2001; Merrill, Levin and Myers, 2004; Heller, 2008). Upstream discoveries waiting for an industrial application slowly gained more and more weight. In the words of Somerville and Lumb (2004), "developers of research tools should also continue giving consideration to 'reach-through' claims covering drug candidates identified by their tool and/or methods of treatment. Such reach-through claims place a prime value on the research tools underlying the drug discovery, enabling the patentee to secure a greater stake in the downstream pharmaceutical development and sales".

[1] "Upstream" is meant to incorporate basic research and early stage development process.

[2] For points 1 and 2, see Author et al. (1998).

[3] Acemoglu (1998 and 2000b) and Kiley (1999) show that education increases the market for the skill complementary inputs, thereby driving up the profitability of innovations that increase the productivity of the skilled and therefore the returns to higher education.

[4] Dinopoulos and Segerstrom (1999) show that the decrease in trade barriers, by enlarging the market size for successful innovation, increases the return to education. This is so because skilled labour is used more intensively in the knowledge creation activities. Sener (2001) reinforced this channel in the presence of unskilled Schumpeterian unemployment.

[5] Cozzi and Impullitti (2009) document a progressive a change in the US government expenditure towards a bigger share of high technology goods; this may have increased the profits of the technologically more dynamic sectors, thereby increasing the returns to college.

[6] Jaffe and Lerner (2006) track the origin of the change in the US innovation environment in the early Eighties and specifically identify a negative role for the US legal framework into bearing the US innovation system through the right system of incentives.

[7] Jensen and Thursby's (2001) empirical study found that the majority of the inventions licensed by US universities in 2001 were in an embryonic state of development ("no more than a proof of concept").

In order to provide new insights on the links between intellectual property, innovation, education and inequality, we combine a closed-country version of Dinopoulos and Segerstrom's (1999) dynamic general equilibrium model with cumulative innovation and educational choice, with a two-stage cumulative innovation structure *a la* Grossman and Shapiro (1987) and Green and Scotchmer (1995).

In our framework, basic and applied research technologies are heterogenous and the bargaining power of the upstream innovation changes[8], thus stylizing the evolution of the US jurisprudence after 1980. From that date on, the US national system of innovation has been re-shaped by a sequence of important new laws and by a cumulative sequence of sentences that set the precedents for future modifications in the jurisprudence. All these changes pointed to an increase in the appropriability of innovations at their initial stages[9]. The pro-early innovation cultural change is also reflected in the increasing protection of trade-secrets - starting in the 80s with the Uniform Trade Secret Act and culminating with the Economic Espionage Act of 1996[10] - as well as in the increasingly positive attitude towards software patents (Hunt, 2001, Hall, 2009), culminating in the Final Computer Related Examination Guidelines issued by the *USPTO* in 1996. Being the US a common-law regime, the jurisprudence evolved gradually[11] in the direction of stricter intellectual protection of research tools, basic research ideas[12], etc. This process took a quarter century, culminating in the 2002 *Madey vs. Duke University* Federal Circuit's decision, which completed a process of elimination of the "research exemption" to patent claims. We conjecture that, along with other factors, it may have contributed to lead the economy along a transition characterized by increasing wage inequality and higher education attainements and innovation, after an initial productivity slowdown.

[8] Our framework somewhat complements Eicher and García-Peñalosa, (2008), that envisages endogenous IPR based on firm choice, instead of on jurisprudence evolution.

[9] Including the Stevenson-Wydler act of 1980 and the Bayh-Dole act, of 1980, amended the patent law, to facilitate the commercialization of inventions obtained thanks to government funding, especially by universities.

[10] See Cozzi (2001) and Cozzi and Spinesi (2006).

[11] In our case, it is important to recall Janice Mueller's (2004) account of the common law development of a narrow experimental use exemption from patent infringement liability: with special reference to the discussion of the change in the doctrine from 1976's *Pitcairn v. United States*, through 1984's Federal Circuit decision of *Roche Products, Inc. v.Bolar Pharmaceutical Co.,* all the way to *Madey v. Duke University* in 2002.

[12] See Gallini (2002), Mueller (2002 and 2004), Scotchmer (2004).

The US legal system, as the legal systems of most of the Commonwealth countries, includes in the list of the sources of right the common law. The essence of the common law is that it is made by judges sitting in courts, by applying their common sense and knowledge of legal precedent (*stare decisis*) to the facts before them. It is founded on the concept of precedence on how the courts have interpreted the law: under common law the decisions are reached by analogy, after comparing the facts of a particular case to similar previous cases. During the early 1980s began a progressive process in which the U.S. Court decisions changed from the old doctrine limiting the patentability of early-stage scientific discoveries to the conception that also fundamental basic scientific findings (such as genetic engineering procedures or semiconductor designs) are patentable. Ideally started in 1980 with the *Diamonds v. Chakrabarty* case, in which the Supreme Court of United States ruled that microorganism produced by genetic engineering could be granted patent protection, according to some authors, this process culminated in 2002 with the well known Federal Circuit decision *Madey v. Duke University*, by which the common law fair use doctrine did not even allow universities to infringe patents on research tools for teaching or experimental purposes (Mueller, 2004).

If what deeply characterizes common law (and sharply separates it from the Continental Europe type legal systems) is an uninterrupted continuity such that within the *stare decisis* regime an institutional break point is even hardly conceivable, we must conclude that the analysis of the effects of the US patent policy on the economy is forced to include the whole transition dynamics. In other words, if the common law shows a strong link with its evolutionary history, we are not dealing anymore with an IPR revolution but with its evolution. Hence, the cumulated stock of courts decisions up to time t determines a flow of new decisions, or, the court's orientation in a given instant of time t depends on the cumulated stock of sentences up to time t. The law and economics literature is currently modelling the evolution of the case law in the perspective of analyzing Benjamin Cardozo's and Richard Posner's view of common law as efficiency promoting. In fact, according to this influential view, unlike civil law, being the common law decentralized, it follows the aggregate decision making of several heterogenous judges, whose idiosyncratic opinions average one another. Moreover, the very sequential precedent structure, implies that (Gennaioli and Shleifer, 2007b) one appellate court overrules another's decision, tending to progressive mitigation and efficiency only if the majority of the judges is unbiased, depending also on the judge's effort cost of changing the legal rule established in a precedent. Appellate courts may change a previously established legal rule also by "distinguishing" the case based on the consideration of a "previously neglected dimension" (Gennaioli and Shleifer, 2007a), which can facilitate convergence towards a more efficient legal rule. Empirical analysis is still scarce, with the notable exeption of Niblett, Posner, and Shleifer's (2008) analysis of the evolution of the Economic Loss Rule (ELR) in the US construction industry from 1970 to 2005, according to which the ELR doctrine seemed to follow a clear increasingly narrow pattern for more than two decades (1970-1993), which was then followed by a subsequent (1994-2004) inverse trend. Based on these analyses, we inquire on whether the increasingly pro-upstream R&D court orientation from 1980 to 2002 has been following an improvement in promoting innovation or if it has ended up following the bias of less and less liberal judges. In this paper, we look for potentially detectable aspects of the time series of several important variables - skill wage premium, education, innovation, labour force allocation, market value of patents, etc. - associated with either long-term evolution of the legal rules. In doing so, we follow a dynamic general equilibrium perspective, which forces us to assume that economic agents are sufficiently intelligent to detect what "trend" is occurring, and suitably take optimizing decisions.

In order to analyze the effects of an expected and progressive change in the patent protection of basic research, we therefore need to simulate all variables in their transitional dynamics. We will extract lessons from our numerical results, useful to detect whether an increasingly more string basic research protection common law doctrine is gradually facilitating the national system of innovation or evolving for the worse.

The remainder of this paper is organized as follows. Section 2 and Section 3 set the model and Section 4 characterizes the equilibrium. Section 5 the growth maximizing steady-state upstream innovator share in a simple special case, useful as a benchmark. In Section 6 we show the numerical simulations. Section 7 concludes.

2 The Model

2.1 Households

We assume a large number of dynastic families, normalized to 1 for simplicity, whose members, born at birth rate $\tilde{\beta}$ and passing away at rate δ, live a period of duration D. The resulting population growth rate[13] is $g = \tilde{\beta} - \delta > 0$. This demographic structure implies the following restrictions: $\tilde{\beta} = \frac{ge^{gD}}{e^{gD}-1}$ and $\delta = \frac{g}{e^{gD}-1}$.

At time t the total number of individuals is e^{gt}. Each individual can spend her life working as unskilled or studying the first $T_r < D$ periods and then working as skilled. Each individual cares only about the utility of the average family member. Hence, despite bounded individual life, the individual decisions are taken within the household by maximizing the following intertemporally additive utility functional:

$$U = \int_0^{\infty} e^{-\rho t} u(t)\, dt, \tag{1}$$

where $\rho > 0$ is the subjective rate of time preference. Per-family member instantaneous utility $u(t)$ is defined as:

$$u(t) = \int_0^1 \ln \left[\sum_j \gamma^j d_{jt}(\omega) \right] d\omega, \tag{2}$$

where $d_{jt}(\omega)$ is the individual consumption of a good of quality $j = 1, 2, ...$ (that is, a product that underwent j quality jumps) and produced in industry ω at time t, and bought at price $p_{jt}(\omega)$. Parameter $\gamma > 1$ measures the size of the quality upgrades.

Defining percapita expenditure on consumption goods as $E(t) = \int_0^1 \left[\sum_j p_{jt}(\omega)\, d_{jt}(\omega) \right] d\omega$, the real interest rate as $i(t)$, and time 0 family wealth as $A(0)$, the intertemporal budget constraint is $\int_0^{\infty} e^{gt - \int_0^t i(\tau) d\tau} E(t)\, dt \leq A(0)$.

Following standard steps of quality ladders models[14], the consumers will only buy good with the lowest quality adjusted price, and the Euler equation follows:

$$\dot{E}(t)/E(t) = i(t) - (\rho + g) = r(t) - \rho, \tag{3}$$

[13] Dinopoulos and Segerstrom (1999) have first develped the overlapping generations education framework followed here. Boucekkine et al. (2002) and Boucekkine et al. (2007) recently studied population and human capital dynamics in continuous time and off steady states and numerically calibrated in a way methodologically more similar to ours.

[14] See Segerstrom et al. (1990), Grossman and Helpman (1991) and Segerstrom (1998).

where $r(t) \equiv i(t) - g$ is the population growth deflated instantaneous market interest rate at time t, and, together with the transversality condition, determines consumer choice.

Individuals differ in their learning ability θ, which, for each generation, is uniformly distributed in the unit interval. Hence an individual of ability $\theta \in [0, 1]$ will be able to acquire $\theta - \Gamma$ units of human capital after an indivisible training period of length T_r. The only cost of education is the individual's time, which prevents her from earning the unskilled wage w_u. In what follows we choose unskilled labour as our numeraire, and therefore set $w_u(t) = 1$ at all $t \geq 0$.

Hence an individual born at t with (known) ability $\theta(t) \in [0, 1]$ and who decides to educate herself will earn nothing from t to $t + T_r$, and then earn a skilled wage flow $(\theta(t) - \Gamma)w_H(s)$ at all dates $s \in [t + T_r, t + D]$, which implies that at time t there will exist an ability threshold $\theta_0(t) \in [\Gamma, 1]$ below which the individual decides to work as an unskilled. Threshold $\theta_0(t)$ solves the following equation:

$$\int_t^{t+D} e^{-\int_t^s i(\tau)d\tau} ds = (\theta_0(t) - \Gamma) \int_{t+Tr}^{t+D} e^{-\int_t^s i(\tau)d\tau} w_H(s)ds,$$

obtaining

$$\theta_0(t) = \Gamma + \frac{\int_t^{t+D} e^{-\int_t^s i(\tau)d\tau} ds}{\int_{t+Tr}^{t+D} e^{-\int_t^s i(\tau)d\tau} w_H(s)ds}. \tag{4}$$

It is important to notice that the ability threshold can change over time, because the future real interest rates $i(t)$ and skilled wage rates $w_H(t)$ are free to change. It is worthwhile to notice that Dinopoulos and Segerstrom's (1999) framework allows for a strong dispersion within the skilled labour group: in fact, $w_H(t)$ is the amount of skilled wage per-efficiency unit of labour, whereas people actual earnings vary with their ability.

Since in a steady state $i(t) = \rho + g$, the steady state level of $\theta_0(t)$ is

$$\theta_0 = \Gamma + \frac{1 - e^{-(\rho+g)D}}{\left[e^{-(\rho+g)Tr} - e^{-(\rho+g)D}\right] w_H}, \tag{5}$$

where w_H denotes the steady state skill premium.

2.2 Manufacturing

In each final good industry $\omega \in [0,1]$ and for each quality level $j(\omega)$ of the good, production is carried out according to the following Cobb-Douglas technology

$$y(\omega,t) = X^{\alpha}(\omega,t)\, M^{1-\alpha}(\omega,t)\,, \text{ for all } \omega \in [0,1], \tag{6}$$

where $\alpha \in (0,1)$, $y(\omega,t)$ is the output flow at time t, $X(\omega,t)$ and $M(\omega,t)$ are the skilled and unskilled labour inputs. In each industry firms minimize costs by choosing input ratios

$$\frac{X(\omega)}{M(\omega)} = \frac{1}{w_H(t)}\,\frac{\alpha}{1-\alpha}. \tag{7}$$

The total percapita amount M of unskilled labour only works in the manufacturing sectors. Therefore the aggregate skilled labour demand is equal to:

$$X(\omega,t) = \frac{1}{w_H(t)}\left(\frac{\alpha}{1-\alpha}\right) M(t)P(t) \tag{8}$$

In percapita terms,

$$x(\omega,t) \equiv \frac{X(\omega,t)}{P(t)} = \frac{1}{w_H(t)}\left(\frac{\alpha}{1-\alpha}\right) M(t) \equiv x(t). \tag{9}$$

As in Aghion and Howitt (1992), skilled labour can also work in the R&D sectors. Therefore, a higher skilled premium $w_H(t)$ frees resources for the R&D sectors.

We assume instantaneous Bertrand competition in all sectors. Since only the owner of the most recent top quality good patent can produce the top quality version of its sector good, the equilibrium price will be equal to a mark-up $\gamma > 1$ over the unit cost $c(w_H(t),1)$. Moreover, being demand unit elastic, percapita demand is $d(t) = \frac{E}{\gamma c(w_H(t),1)}$. Therefore is each sector the temporary monopolist who owns the top quality product patent earns the same profit which, in percapita terms, is equal to[15]:

$$\begin{aligned} \pi(t) &= \frac{\gamma-1}{\gamma}E(t) = (\gamma-1)\frac{w_H(t)x(t)}{\alpha} = \\ &= (\gamma-1)\frac{1}{1-\alpha}m(t). \end{aligned} \tag{10}$$

3 R&D and Innovation

The quality level j of each final product of variety $\omega \in [0,1]$ can increase as a result of R&D undertaken by private firms. In order to capture the interaction between basic and applied research[16], we assume - as in Cozzi and Galli (2008) - that a basic research idea is a pre-requisite to applied research and applied R&D success opens the door for a further basic research advance. Hence, the innovative process leading to a final product quality is, as in Grossman and Shapiro (1987), a two-stage process: in the first stage R&D discovers a pure idea; in the second stage R&D embodies that idea into a new product. The first stage - basic research - of the product quality jump is the outcome of a Poisson process with probability intensity $\frac{\lambda_0}{P(t)}\left(\frac{N_B(\omega,t)}{P(t)}\right)^{-a}$ per unit of research labour, where $\lambda_0 > 0$ is a basic research productivity parameter, $N_B(\omega,t)$ is the mass of research labour employed in sector ω at time t, and $a > 0$ is a congestions externality parameter. The presence of population size, $P(t)$, in the denominator states that R&D difficulty increases with the total population in the economy[17], which delivers endogenous growth with-

[15] The second equality builds on the Cobb-Douglas property that minimum total cost is $\left[\left(\frac{1-\alpha}{\alpha}\right)^{-(1-\alpha)} + \left(\frac{\alpha}{1-\alpha}\right)^{-\alpha}\right] w_s^{\alpha} w_u^{1-\alpha} X^{\alpha}(\omega) M^{1-\alpha}(\omega)$. Hence profit is $(\gamma-1)$ times total cost. Using eq. (8) and simplifying gives the result.

[16] According to Nelson (1959) and (2006), basic R&D is not only a source of inspiration for applied R&D, but also continuously inspired by applied R&D, which raises important questions on why some new discoveries actually work. This second point is also modelled by Howitt (1999), when knowledge frontier advances are a result of applied R&D success frequencies.

[17] Population density favour innovation at the local level (see Hunt, Chatterjee, and Carlino, 2001): according to this solution to the strong scale effect, the dilution of R&D is not related to population density, but with the overall size of the economy.

out the strong scale effect[18], as suggested by Smulders and Van de Klundert (1995), Young (1998), Peretto (1998 and 1999), Dinopoulos and Thompson (1998), Howitt (1999), and recently confirmed empirically by Ha and Howitt (2006) and Madsen (2008).

The second stage - applied research - completes the basic research idea and generates the new higher quality produceable good according to a Poisson process with probability intensity $\frac{\lambda_1(t)}{P(t)}\left(\frac{N_A(\omega,t)}{P(t)}\right)^{-a}$ per unit of research labour, where $\lambda_1(t) > 0$ is an applied research productivity, viewed by the fims as a constant; $N_A(\omega, t)$ is the mass of research labour employed in sector ω at time t; and $a > 0$ is the congestions externality parameter.

Defining $n_B(\omega, t) \equiv \frac{N_B(\omega,t)}{P(t)}$ and $n_A(\omega, t) \equiv \frac{N_A(\omega,t)}{P(t)}$, as the skilled labor employment in each basic and, respectively, applied R&D sector, we can express the expected innovation rate in a ω' sector undertaking only basic R&D as $\lambda_0 n_B(\omega', t)^{1-a}$ and the expected innovation rate in a ω'' sector undertaking only applied R&D as $\lambda_1(t)n_A(\omega'', t)^{1-a}$. All stochastic processes are independent both across sectors and across firms. Hence, the existence of a continuum of sectors implies that the law of large number applies and aggregate variables evolve deterministically. Since all sectors switch from hosting only basic R&D firms - belonging to subset $A_0(t) \subset [0, 1]$ - to hosting only applied R&D - belonging to subset $A_1(t) \subset [0, 1]$ - the mass of sectors belonging to each type will flow deterministically[19]. Notice that $A_0(t) \cup A_1(t) = [0, 1]$ and $A_0(t) \cap A_1(t) = \emptyset$. Moreover, in our model, symmetric equilibria exist, allowing us to simplify notation: $n_B(\omega, t) \equiv n_B(t)$ and $n_A(\omega, t) \equiv n_A(t)$. Therefore, if $m(A_0(t)) \in]0, 1[$ is the Lebesgue mass of the $A_0(t)$ subset - and hence $m(A_1(t)) = 1 - m(A_0(t))$ the Lebesgue mass of $A_1(t)$ subset - its evolution would be deterministic and described by the following first order differential equation:

$$\frac{dm(A_0(t))}{dt} = (1 - m(A_0(t)))\,\lambda_1(t)\,(n_A(t))^{1-a} - m(A_0(t))\lambda_0\,(n_B(t))^{1-a}. \quad (11)$$

In order to truly capture the distinction between pioneering and follow-on innovations, in this paper - unlike in Cozzi and Galli (2008) - we follow the literature, by thinking of pioneering inventions as ones that generate more

[18] See Dinopoulos and Thompson (1999) and Jones (2005).

[19] Provided the initial mass Lebesgue mass of each was positive.

spillovers or are in some sense "more important" than the subsequent follow on innovations. We assume that the aggregate output of basic research increases the productivity of applied research: $\lambda_1(t) = \overline{\lambda}_1 \left(1 + \lambda_0 \left[\int_0^1 n_B(\omega, t) d\omega\right]^{1-a}\right)^{\varphi}$, where $\overline{\lambda}_1$ and φ are positive constants. This formulation introduces the possibility of cross-fertilization of applied research by other sector's basic research findings[20]. In symmetric equilibrium $\lambda_1(t) = \overline{\lambda}_1 \left(1 + \lambda_0 \left[n_B(t)\right]^{1-a}\right)^{\varphi}$.

We assume free entry into basic and applied research. Each inventor, be she basic or applied, is granted a patent. However, though the first R&D firm that invents a new final product gets the patent anyway, it will infringe the patent held by the previous basic research inventor. Therefore it will have to bargain with the basic research patent holder in order to produce the new version of this good.

Such a framework, corresponding to Green and Scotchmer (1995) research exemption regime for pure research tools[21], captures important aspects of the real world disputes between inventors whose patent claims allow the blocking of invention[22]. The share, $\beta(t) \in]0, 1[$, of the final product (applied) patent value assigned - at the end of the negotiations taking place at time t - to the upstream (basic) patent holder[23] captures time t court orientation towards intellectual property. New laws, patent law amendments, changes in the jurisprudence towards stronger patent claims and weakening research exemptions would correspond to increases in $\beta(t)$, whereas a gradually looser upstream patent holder protection and stronger research exemptions would correspond to a declining $\beta(t)$. In the rest of the paper we will consider

[20] This is complementary to Howitt's (1999) assumption of general knowledge, $A_t^{\max}$, being positively affected by the aggregate applied R&D.

[21] Also see Scotchmer (2004) and Nagaoka and Aoki (2006) for microeconomic analysis of this important case.

[22] O'Donoghue (1997), O'Donoghue et al. (1998), and O'Donoghue and Zweimueller (2004) are indirectly related, as they capture the role of patent claims in molding the bargaining between current and future innovators: their concepts of patentability requirement and leading breadth could be re-adapted here to accomodate the blocking power of the upstream patent holder.

[23] Assuming that basic and applied innovators matched and targeted applied innovator-specific innovations, could re-read this strategic interaction as Aghion and Tirole's (1994a and b) research unit (RU) and customer (C). Then our case would clearly correspond to when RU's effort is important ($\tilde{U}_C > U_C$), which implies that "the property right is allocated to RU" (Aghion and Tirole, 1994b, p. 1191). In this light, our $\beta(t)$ generalizes Aghion and Tirole's (1994a and b) equal split assumption.

gradual changes in patent policy in terms of the sign of $\dot{\beta}(t)$. In fact, we assume that the following holds:

$$\dot{\beta}(t) = (1 - \psi)(\bar{\beta} - \beta(t)). \tag{12}$$

Equation (12) is a linear differential equation with constant coefficient, which describes the speed of change in $\beta(t)$ per unit time. Parameter $\psi < 1$ guarantees asymptotic stability and $\bar{\beta} \in]0, 1[$ is the steady state. We will consider the progressive tightening of intellectual property rights in the US as the result of a sudden change in $\bar{\beta}$, which determines a gradual increase in $\beta(t)$ from its previous lower steady state level to its new level. It is important to notice that we are in a rational expectation framework: all economic agents after the regime change can predict the successive increases in $\beta(t)$, and the transition to a tight IPR regime is known to the agents from the beginning and all decisions are re-optimized. Hence all our numerical simulations are immune to Lucas' critique, unlike other models that, albeit assuming dynamic general equilibrium, treat the gradual policy changes as a sequence of surprises. The reason why we think our approach is appropriate is that from 1980 on IPR policy has steadily and progressively been tightening and progressively become more and more biased toward earlier innovator. This steady upstream shift of innovation incentives was too regular not to be incorporated in people's expectations[24], which leads law scholars to view 1980 as a sort of structural break of equation (12), and forces us to study the whole transitional dynamics of the model's economy. The statutory decisions taken in the early 1980 triggered a gradual change in the common law[25]. Maybe that exogenous technological-scientific modifications were taking place which imposed statutory intervention to change an otherwise binding set of precedents[26]: this has inagurated the new era, which would be represented by an

[24]Unless focussing attention only on a short time span, as in Cozzi and Galli (2008) and Aghion et al. (2008).

[25]According to Fon and Parisi (2006), such a case evolution could also appear in a civil law system.

[26]"Second, it may be impossible to reverse the precedents of the past when changing economic conditions warrant such a reversal. Precedent tends to weigh heavily upon decisions of the court, as perhaps it should. But rulings of a century ago, say on questions of pollution, may not be optimal today. If the bias imparted by precedent is too great, however, a change in precedent may be impossible, even if" it would be beneficial to many parties involved (Goodman, 1978, p. 406).

increase in $\bar{\beta}$ and a resulting re-adjustment of the judicial system, thereby dragging the whole macroeconomy.

4 Equilibrium

In this section we keep time notation, because, since we are considering dynamic general equilibrium, all endogenous variable can change over time, as will be shown in the numerical simulations.

Let us definel v_B,v_L^0, and v_L^1 as the present expected value of a basic research patent (v_B), of an A_0 industry quality leader (v_L^0), and of an A_1 industry challenged leader (v_L^1).

Costless arbitrage between risk free activities and firms' equities imply that in equilibrium at each instant the following equations shall hold:

$$w_H(t) = \lambda_0 n_B(t)^{-a} v_B(t) \tag{13a}$$

$$r(t)v_B(t) = \lambda_1(t) n_A(t)^{1-a} \left(\beta(t) v_L^0(t) - v_B(t)\right) + \frac{dv_B(t)}{dt} \tag{13b}$$

$$w_H(t) = \lambda_1(t) n_A(t)^{-a} \left(1-\beta(t)\right) v_L^0(t) \tag{13c}$$

$$r(t)v_L^0(t) = \pi(t) - \lambda_0 n_B(t)^{1-a} \left(v_L^0(t) - v_L^1(t)\right) + \frac{dv_L^0(t)}{dt} \tag{13d}$$

$$r(t)v_L^1(t) = \pi(t) - \lambda_1(t) n_A(t)^{1-a} v_L^1(t) + \frac{dv_L^1(t)}{dt} \tag{13e}$$

The value of a monopolist in an A_0 industry, v_L^0, has to obey equation (13d): in fact, the shareholders of the current quality leader compare the (population growth adjusted) risk free income, rv_L^0, obtainable from selling their shares and buying risk free bonds to the expected value of their profits, π, net of probable capital loss, $\lambda_0 n_B^{1-a}\left(v_L^0 - v_L^1\right)$, in case a new basic research result appears in the industry. Since we assume perfect and costless financial markets, all idiosyncratic risk is diversified away and investors only compare expected returns.

As soon as a new basic R&D result appears in the industry, the incumbent monopolist's value falls down to a lower, but still positive, value v_L^1, which has to obey eq. (13e): as before, risk free income is equated to expected profits net of expected capital loss, but now the probability of the basic research idea's being completed by applied research in the industry, $\lambda_1 n_A^{1-a}$, is the monopolistic profit hazard rate, as the arrival of the new final product implies the complete displacement of the current leading edge product.

Equation (13a) characterizes free entry into basic R&D (in an A_0 industry), equalizing the skilled wage to the probability $\lambda_0 n_O^{-a}$ of inventing times the value v_B of the resulting patent.

Equation (13b) equated the risk free income from selling a basic R&D patent, rv_B, to the expected present value of holding it in an A_1 industry. These expected increase in value deriving from someone else's - the n_A downstream researchers' - discovering the industrial application, of value v_L^0, plus the gradual appreciation in the case of someone else's R&D success not arriving, $\frac{dv_B}{dt}$.

Equation (13c) is the free entry condition for downstream completers that rationally expect to appropriate only fraction $1-\beta$ of the value of the final good monopolist.

As in the previous section, the industrial dynamics of this economy is described by the following first order ordinary differential equation:

$$\frac{dm(A_0(t))}{dt} = (1 - m(A_0(t)))\,\lambda_1(t)\,(n_A(t))^{1-a} - m(A_0(t))\lambda_0\,(n_B(t))^{1-a}. \quad (14)$$

These equations must be supplemented with the skilled labour market equilibrium condition

$$x(t) + m(A_0(t))n_B(t) + (1 - m(A_0(t)))\,n_A(t) = h(t), \quad (15)$$

where $h(t) \equiv H(t)/P(t)$ is the aggregate population-adjusted human capital.

5 Analysis of a Benchmark Special Case

Though the numerical simulations of Section 6 will illustrate the main properties of our economy, it is useful to provide some qualitative analysis under special parameter conditions. The results of this sections are obtained under the assumption that $\rho = 0$, which greatly facilitates the analytical derivations. Since all steady state equations are continuous in all variables and parameters, the sign of the derivatives of the steady state equilibrium endogenous variables remain unaltered in a positive neighborhood where $i > 0$. Notice that in the steady state the real interest rate is $i = r + g$, and our assumption implies $i = g > 0$. Hence equations where ρ appears do not formally change[27]. For simplicity, we will also assume $\varphi = 0$: this eliminates the externality of basic research on applied research.

Notice that eq. (13b), the steady state definition and $r = 0$ imply:

$$v_B = \beta v_L^0.$$

From this and from eq.s (13a) and (13c):

$$n_A = \left(\frac{\lambda_1}{\lambda_0} \frac{1-\beta}{\beta} \right)^{\frac{1}{a}} n_B. \tag{16}$$

This confirms Denicolo's (2000) Proposition 1 in our extended framework. From equations (13d) and (13e), the steady state definition and $r = 0$ we can write:

$$v_L^0 = \left[\left(\frac{\lambda_1}{\lambda_0} \right)^{\frac{1}{a}} \left(\frac{1-\beta}{\beta} \right)^{\frac{1-a}{a}} + 1 \right] v_L^1. \tag{17}$$

Imposing the steady state into (14) and using (16) yields:

Lemma 1. *The steady state equilibrium fraction of industries where basic R&D is active is*

$$m(A_0) = \frac{1}{1 + \left(\frac{\lambda_0}{\lambda_1} \right)^{\frac{1}{a}} \left(\frac{\beta}{1-\beta} \right)^{\frac{1-a}{a}}}. \tag{18}$$

Remark. What Lemma 1 states is that the higher the difficulty of basic research (applied research), i.e. the lower λ_0 (the lower λ_1) the higher the fraction of sectors where basic (applied) R&D is needed.

This has implications for R&D enhancing regulation:

Proposition 1. *The growth maximizing upstream inventor share, β^*, of the final good patent value is equal to:*

[27] More generally, even assuming $g = 0$, and therefore $\rho = 0$ would not imply complications, as straightforward application of De L'Hospital's theorem would imply $lim_{\rho \to 0} \theta_0 = \gamma + \frac{D}{(D-Tr)w_H}$.

$$\beta^* = \frac{\lambda_1}{\lambda_0 + \lambda_1} = \frac{1}{\frac{\lambda_0}{\lambda_1} + 1}. \tag{19}$$

Proof. See Appendix.

Remark. Our analysis implies that innovation-maximizing basic research patent claims should be neither too broad nor too narrow. Since in this example time costs nothing, both applied (direct) and basic (indirect) research should be given equal reward if their R&D technologies are the same ($\lambda_0 = \lambda_1$). Interestingly, Green and Scotchmer's (1995) and Scotchmer's (2004) benchmark parameter value is $\frac{1}{2}$, as well as Aghion and Tirole's (1994a and b) equal split assumption. A similar assumption was made by Denicolo's (2000) patentable and infringing (PI) second-stage innovation. In our perpetual innovation framework, as ρ increases basic research should be compensated more in order to maximize growth.

Proposition 1 states that the innovators should be rewarded proportionally more in the stages of R&D where innovation is harder to achieve. Plugging β^* into eq. (16) implies that at the optimal policy $n_A = n_B$. Hence the optimal share is higher in the (sub-)industries where (equilibrium) innovation is slower - expected times $\frac{1}{\lambda_0 n_B^{1-a}} > \frac{1}{\lambda_1 n_A^{1-a}}$ imply $\beta^* > 0.5$ and viceversa - which is consistent with Hunt's (2004) testable implication for innovation promoting patentability standards[28].

Our analysis is also related to Hunt (2006), in which each duopolist, when obtaining a patent, get a ticket to sue the rival and to grab a share $0 < \beta < 1$ of the value of its innovation. In his model, Hunt proves that if β is relatively too high the increase in patent protection discourages R&D. Here we follow a similar logic, though in a sequential framework: endowed with too much bargaining power, the basic research patent holder may end up capturing too a large part of the downstream innovation, thereby discouraging total R&D.

6 Numerical Simulations

In this section we illustrate representative time trajectories of endogenous variables following the announcement of a regime change in the law of motion

[28] An interesting extension of our paper would be obtained by breaking the symmetry assumption over the product space.

of the share of the final value of applied R&D that will be assigned to the basic researcher. This corresponds to a sudden change in the steady state value of eq. (12) that gradually drives the system towards the new steady state. We ran several discrete approximations of the differential equations (27), (30), (12), (33), (13b), (13d), (13e), (39),(40), (37), (38), (14), and cross-equations restrictions (13a), (13c), (9), (10), (15), and (34), obtaining quite regular results.

We also assume that, in our common law regime, the policy/courts orientation change is not only gradual but also expected ahead of time. In the figures that follow we show the simulations obtained for the following parameter values: $\alpha = 0.1$, $a = 0.3$, $\gamma = 1.68$, $\lambda_0 = \bar{\lambda}_1 = 1$, $\varphi = 0.01$, $D = 40$, $n = 0.01$, $r = 0.05$, $T_r = 4$, $\Gamma = 0.75$, which are standard in the literature. As for the common law adjustment parameter, we set $\psi = 0.9$. After running several simulations, we realized that the interest rate did not change at all. Moreover, no difference in the qualitative and little quantitative difference was associated with robustness analysis: for example, setting $\varphi = 0$ through $\varphi = 1$ did not change almost anything.

We assume that the economy begins with a steady state associated with a given value of $\bar{\beta}$. Then $\bar{\beta}$ changes and the common law share of the basic research inventor starts to head to its new steady state value.

In order to make different simulations comparable, we plot the trajectories of the deviations of the value of each variable from its initial steady state value, divided by its initial steady state value.

Figure 1 assumes that, after a long term (40 periods) initial value of $\bar{\beta} = 0.35$, it suddenly changes to $\bar{\beta} = 0.5$. By As a consequence of Proposition 1, such a change will be beneficial for long term growth.

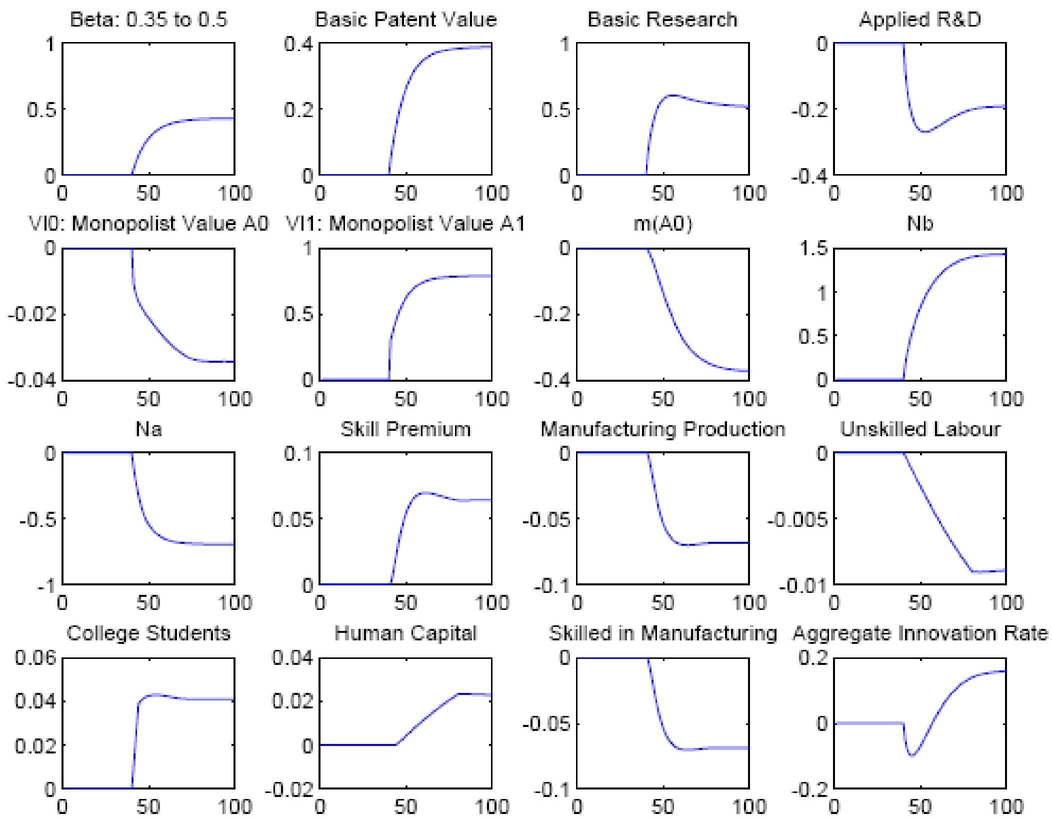

Beta: 0.35 to 0.5
Basic Patent Value
Basic Research
Applied R&D
VI0: Monopolist Value A0
VI1: Monopolist Value A1
m(A0)
Nb
Na
Skill Premium
Manufacturing Production
Unskilled Labour
College Students
Human Capital
Skilled in Manufacturing
Aggregate Innovation Rate

Figure 1

Such a change is clearly growth improving from a steady state perspective: in the long run the new steady state is characterized by a higher rate of aggregate growth, a higher skill premium, a higher fraction of population choosing to educate themselves ("college students") and a higher aggregate human capital. A higher value of β means a higher fraction of the final invention appropriated by the basic researcher who invented its basic research prerequisite and a lower value of the final product appropriated by the applied researcher who invented its commerciable version. Therefore basic research is becoming more profitable (higher "Basic Patent Value", v_B) and applied research less profitable. Consequently basic research employment increases - both at the aggregate ("Basic Research") and at the industry, ("Nb") level - and applied research employment decreases both at the aggregate ("Applied R&D") and at the industry, ("Na") level. A consequence of this is that in the long run the stock market value (v_L^1) of an A_1 monopolist increases - as it faces less obsolescence - while the long run the stock market value (v_L^0) of an A_0 monopolist decreases, as it faces more obsolescence. Since the positive incentives to basic R&D outweigh the negative incentives to applied R&D, R&D becomes more profitable and more skilled labour is demanded. Therefore the skill premium, w_H, increases as well as the present discounted value of high skill labour, thereby inducing a larger fraction of the population to enrol at university. This will gradually increase the supply of human capital and decrease the supply of unskilled labour.

In the transitional dynamics, it is important to notice that as the change in the long-term court orientation $\bar{\beta}$ is forecast by the private actors, all the stock variables - $\beta(t)$, $h(t)$, $m(t)$, and $m(A_0(t))$ - are predetermined, and for example by eq. (10), $\pi(t)$ is constant. Hence only jump variables such a prices, wages, and employment change. Being $\beta(t)$ monotonically increasing, the relative incentives of basic versus applied research are gradually changed in favor of basic and to the detriment of applied research. However, the dynamics of $\beta(t)$ interacts with the intrinsically dynamic nature of the R&D process, in a way that is not captured by the mere comparative statics of steady state analysis: in fact, the expectation of higher future values of $\beta(t)$ certainly favours current basic research - the completion of which will take place in the future - without harming current applied R&D with the same intensity. To fix ideas, imagine that basic research takes place in one period, as does applied research: the announcement of a higher β next period does not penalise current applied R&D while instead encouraging current basic research - which is promised a higher share of the future discovery. In our continuous time framework the same effect is at work: the two-stage Poisson process of our Grossman and Shapiro's (1987) framework implies that periods are stochastic in length and meanwhile $\dot{\beta}(t) > 0$ favours the expectedly late fruits of basic research more than it reduces the expectedly earliers gains of applied research. As a consequence, aggregate R&D is favoured, and the increase in the demand for $n_B(t)$ is matched by a lower decrease in the demand for $n_A(t)$, which implies that the difference $m(A_0(t))n_B(t) - [1 - m(A_0(t))]\, n_A(t)$ increases and must be matched by a decrease in $x(t)$: the increase in the net demand for R&D labour can be satisfied only by a decrease in the manufacturing skilled-labour employment. This temporary excess demand for skilled labour is the reason for the immediate increase the skill premium. As time passes, the increase in $w(t)$ will encourage marginally able students to enroll to college, thereby leading to a future increase in the the aggregate supply of human capital and to a partially offsetting effect on $w(t)$. However, as long as $\beta(t)$ keeps increasing the demand for R&D labour continues to grow, though the decline in $\dot{\beta}(t)$ will eventually correct the previously mentioned intertemporal asymmetry that favoured basic research more than it disincentived applied R&D.

Interestingly, the aggregate innovation rate initially decreases: the reason is that R&D is shifting upstream towards basic research, thereby reducing applied R&D; this slows down the completion of existing basic research projects, which has a negative effect on innovation. However, in the longer run, the increase in the flow of basic research results will more than compensate a thinner applied R&D effort.

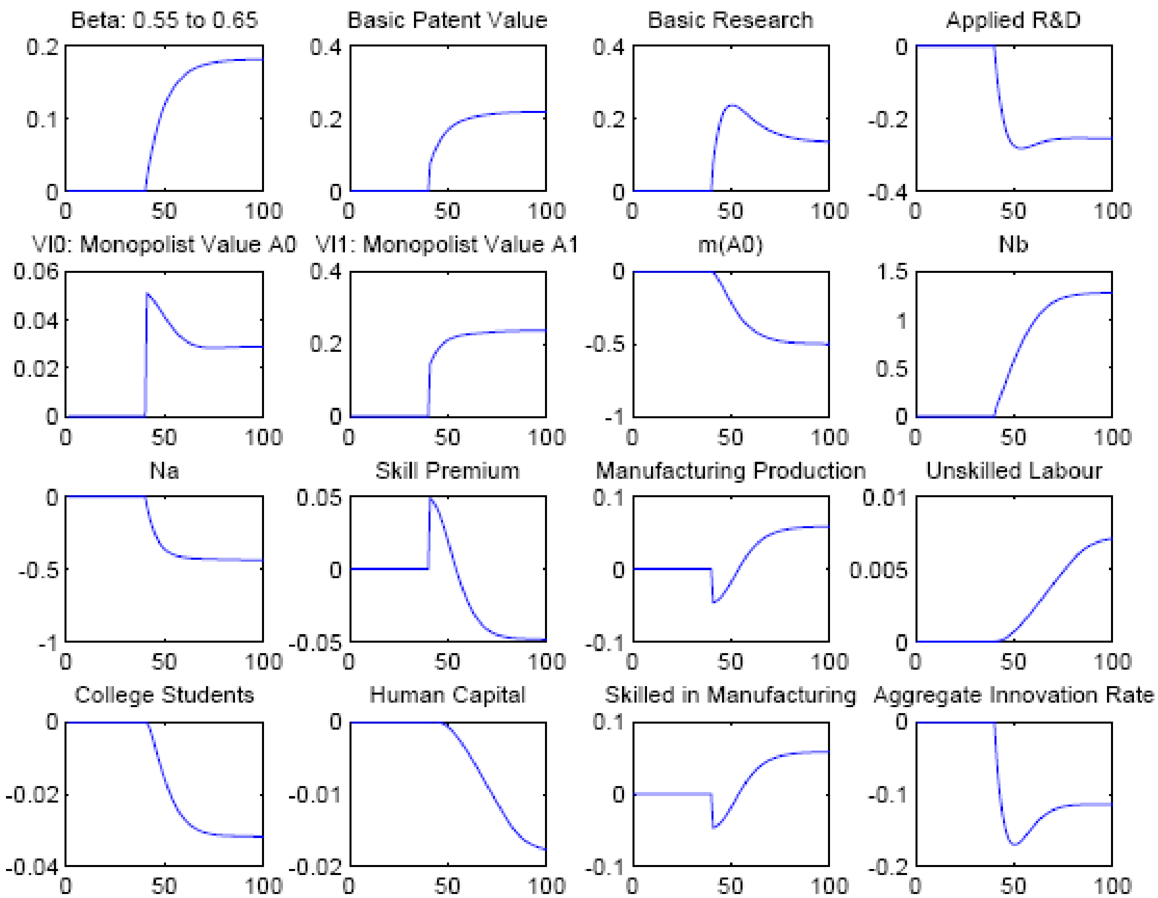
It is interesting to observe an initial slump in innovation follows the beneficial increase in IPR, which may resemble the puzzling "productivity slowdown" measured in the US during the early Eighties[29]. Our stylized representation suggest that economists should not lose their optimism about innovation enhancing policies based on shorter term R&D riallocation effects coupled with improvements in the population educational choices. Notice that this explanation of the productivity slowdown complements the observation of GDP decrease associated to the mere reduction in manufacturing production $x(t)$, which is a consequence of the reduction in available inputs (skilled labour) and therefore not accounted for by the Solow residual[30]

[29] Of course, other important explanations, based on ITC or on adjustment costs, are not contradicted by our analysis.

[30] Clearly, in our model the Solow residual is constant, in so far as we stick to the as-

Figure 2 assumes that the initial value of $\bar{\beta}$ was 0.55 and it suddenly changes to 0.65. Such a change will be detrimental to long term growth, because the basic research patent owner gets entitled to too large a share of the final invention value. This discourages applied R&D too much, which more than offsets the increase in basic research. Therefore the demand for skilled labour will fall and so will the skill premium and education.

sumption of quality improving innovation in the final good sectors. However, following Grossman and Helpman (1991), we could easily re-interprete our model in terms of intermediate good quality improvements. In that case, the innovation slowdown corresponds to the measured productivity slowdown based on Solow decomposition of the increase in output, after accounting for the increase in unskilled and skilled labour inputs.



Beta: 0.55 to 0.65
Basic Patent Value
Basic Research
Applied R&D
Vl0: Monopolist Value A0
Vl1: Monopolist Value A1
m(A0)
Nb
Na
Skill Premium
Manufacturing Production
Unskilled Labour
College Students
Human Capital
Skilled in Manufacturing
Aggregate Innovation Rate

Figure 2

Interestingly, the short term reactions of the skill premium and of manufacturing production could inspire wrong interpretations of the true long term effect of normative changes. In fact, as in the previous discussion, upon impact all stock variables are given, and mainly short term announcement effects prevail. Most notably, the expected gradual increase in $\beta(t)$ fails to penalize current applied R&D in the order of magnitude as it favours current basic research: basic R&D will be entitled of a larger share of the results of *future* applied R&D, not those of current applied R&D. Such temporary win-win situation boosts aggregate R&D labour and therefore raises the skill premium. However, as $\dot{\beta}(t)$ sets in, the temporary relief for applied R&D disappears, and its smaller share of the final product patent penalizes it so much that the ensuing drop in R&D employment outweighs the increase in basic research employment - the whole effect being corroborated by the gradual increase in $1-m(A_0(t))$ - dragging the skill premium below the initial steady state level and therefore leading towards the new steady state, characterized by less R&D employment and less innovation.

We remark that our simulations cast doubt on empirical evaluations of narrowing IPR policies based on relatively short term effects. The short term effects of a harmful tightening of upstream IPR look misleadingly similar to those of a beneficial bargaining power transfer towards basic researcher institutions.

The figures shown in this section are considerably robust and representative of the pro-upstream IPR changes mentioned so far: changing parameters we have observed very similar patterns of short, medium and long run dynamics[31].

7 Conclusions

The possibility that in the real world innovators may use the patents they hold just to block future innovators, and/or prevent them from commercialising their products, raised a still increasing concern[32] not only among academics. The adoption by the US patent law of a statutory research ex-

[31] The files used to generate them are available to the interested readers.

[32] Heller and Eisemberg (1998) suggested the existence of a *tragedy of the anticommons*, i.e. a proliferation of upstream intellectual property rights which greatly amplify the transaction cost of downstream R&D, thus hampering downstream research for biomedical advance.

emption has been proposed as a definitive solution to this problem. But, by postponing bargaining between innovators it may put the downstream inventor at disadvantage and, as Susanne Scotchmer argued, "counterintuitively, a research exemption on first innovation works to benefits of its owner". This paper has tried to tackle these important issues from a macroeconomic perspective.

We have shown how the gradual evolution that characterizes the common law system implies gradual dynamics of the allocation of R&D, human capital, innovation and wage inequality. In light of well known evidence of the steady increase in the skill premium and in education that has been occurring in the Eighties and Nineties in the US and that set the basis for the parallel innovative boom, our simulations suggest that the driving force could have consisted in a beneficial gradual change of the court orientation, in favour of more protection of previously under-protected early stage innovators. On the other hand, should at some point early stage innovators become too protected, opposite trends could appear, as illustrated in Figure 2.

Since the common law system implies gradual change to new IPR regimes, we have been forced to study the whole transitional dynamics. The transition to a stricter regime does not appear to always be monotonic, which shows how assessments based on short term data could be mis-leading. For example, beneficial restrictions in IPR may result in a temporary reduction in innovation, which may seem a bizarre productivity slowdown.

8 Appendix

Proof of Proposition 1. From eq. (32) and (5) follows that the steady state level of human capital percapita is an increasing function of the skilled premium w_H, which we can write as $\overline{h}(w_H)$.

Plugging eq. (16) into the skilled labour market clearing condition (15) yield:

$$\left[m(A_0) + (1 - m(A_0)) \left(\frac{\lambda_1}{\lambda_0}\frac{1-\beta}{\beta}\right)^{\frac{1}{a}}\right] n_B = \overline{h}(w_H) - x(w_H) \equiv \Psi(w_H) \quad (20)$$

with $\Psi'(w_H) > 0$. Inserting eq. (18) into (20) we obtain:

$$\frac{n_B}{\beta\left[1+\left(\frac{\lambda_0}{\lambda_1}\right)^{\frac{1}{a}}\left(\frac{\beta}{1-\beta}\right)^{\frac{1-a}{a}}\right]} = \overline{h}(w_H) - x(w_H) \equiv \Psi(w_H) \tag{21}$$

Plugging eq. (17) into eq. (13a) and (13e) we obtain:

$$w_H = \lambda_0 n_B^{-a}\beta v_L^0 = \lambda_0 n_B^{-a}\beta\left[\left(\frac{\lambda_1}{\lambda_0}\right)^{\frac{1}{a}}\left(\frac{1-\beta}{\beta}\right)^{\frac{1-a}{a}}+1\right]v_L^1 \tag{22a}$$

$$\pi = \lambda_1 n_A^{1-a}v_L^1 = \lambda_1\left(\frac{\lambda_1}{\lambda_0}\frac{1-\beta}{\beta}\right)^{\frac{1-a}{a}} n_B^{1-a}v_L^1 \tag{22b}$$

From the definition of profits and the steady state mass of unskilled labour, we know that $\pi = \pi(w_H)$, with $\pi'(w_H) < 0$. Dividing the last two equations side by side implies:

$$n_B\frac{1}{\beta\left[1+\left(\frac{\lambda_0}{\lambda_1}\right)^{\frac{1}{a}}\left(\frac{\beta}{1-\beta}\right)^{\frac{1-a}{a}}\right]} = \frac{\pi(w_H)}{w_H}. \tag{23}$$

Plugging (23) into (21) gives:

$$1 = \Psi(w_H)\frac{w_H}{\pi(w_H)} \equiv \Phi(w_H) \tag{24}$$

where $\Phi'(w_H) > 0$. Therefore there exists a unique steady state level of the skill premium obtained as the solution to eq. (24). It is important to notice that, in this example, the steady state skill premium is independent of β.

The steady state innovation rate can be rewritten, after using (23), as:

$$\lambda_0 n_B^{1-a}m(A_0) = \frac{\left[\frac{\pi(w_H)}{w_H}\right]^{1-a}\beta^{1-a}}{\left[1+\left(\frac{\lambda_0}{\lambda_1}\right)^{\frac{1}{a}}\left(\frac{\beta}{1-\beta}\right)^{\frac{1-a}{a}}\right]^a} = \tag{25}$$

$$= \frac{\left[\frac{\pi(w_H)}{w_H}\right]^{1-a}}{\left[\left(\frac{1}{\lambda_0}\right)^{\frac{1}{a}}\left(\frac{1}{\beta}\right)^{\frac{1-a}{a}}+\left(\frac{1}{\lambda_1}\right)^{\frac{1}{a}}\left(\frac{1}{1-\beta}\right)^{\frac{1-a}{a}}\right]^a} \tag{26}$$

The numerator does not change with β as previously proved. The innovation rate is maximized when the denominator is minimized. Hence we need to find a value of β such that $\left(\frac{1}{\lambda_0}\right)^{\frac{1}{a}}\left(\frac{1}{\beta}\right)^{\frac{1-a}{a}}+\left(\frac{1}{\lambda_1}\right)^{\frac{1}{a}}\left(\frac{1}{1-\beta}\right)^{\frac{1-a}{a}}$ is minimized, which implies expression (19).QED.

8.1 Labour Supply and Education Dynamics

8.1.1 Unskilled Labor Supply

As previously shown, individuals born at t with ability $\theta(t) \in [0, \theta_0(t)]$ optimally choose not to educate themselves, thereby immediately joining the unskilled labour force. Hence a fraction $\theta_0(t)$ of cohort t remains unskilled their whole life. Summing up over all the older unskilled who are still alive - hence born in the time interval $[t-D, t]$ - we obtain the total stock of unskilled labour as of time t:

$$M(t) = \int_{t-D}^{t} \tilde{\beta} N(s)\theta_0(s)ds = \tilde{\beta} \int_{t-D}^{t} e^{gs}\theta_0(s)ds$$

where $\tilde{\beta}$ is the birth rate, $N(s)$ is the population at time s.

To stationarize variables, we divide by current (time t) population e^{gs}, obtaining:

$$m(t) \equiv \frac{M(t)}{N(t)} = \tilde{\beta} \int_{t-D}^{t} e^{g(s-t)}\theta_0(s)ds.$$

Its steady state level is:

$$m = \tilde{\beta}\frac{1-e^{g(-D)}}{g}\theta_0 = \theta_0.$$

The change in the stock of the population-adjusted stock of unskilled labour is obtained by derivating $m(t)$ with respect to time:

$$\dot{m}(t) = \tilde{\beta}\theta_0(t) - \tilde{\beta}e^{-gD}\theta_0(t-D) - gm(t) \tag{27}$$

As in Boucekkine et al. (2002) and Boucekkine et al. (2007) we obtain a crucial role for delayed differential equations.

8.1.2 College Population

The individuals born in t with ability $\theta(t) \in [\theta_0(t), 1]$ optimally choose to educate themselves, thereby becoming college students for a training period of duration Tr. Hence summing up over all the previous cohorts who are still in college - hence born in the time interval $[t - Tr, t]$ - we obtain the total stock of college population as of time t:

$$\widetilde{C}(t) = \tilde{\beta} \int_{t-Tr}^{t} N(s)(1 - \theta_0(s))ds = \tilde{\beta} \int_{t-Tr}^{t} e^{gs}(1 - \theta_0(s))ds.$$

In percapita terms:

$$\widetilde{c}(t) \equiv \frac{\widetilde{C}(t)}{N(t)} = \tilde{\beta} \int_{t-Tr}^{t} \frac{N(s)}{N(t)}(1-\theta_0(s))ds = \tilde{\beta} \int_{t-Tr}^{t} e^{g(s-t)}(1-\theta_0(s))ds. \quad (28)$$

In a steady state:

$$\widetilde{c} = \tilde{\beta} \frac{1 - e^{g(-Tr)}}{g}(1 - \theta_0). \quad (29)$$

Taking the derivative of eq. (28) with respect to time we obtain:

$$\dot{\widetilde{c}}(t) = \tilde{\beta}\,(1 - \theta_0(t)) - \tilde{\beta} e^{-gTr}\,(1 - \theta_0(t - D)) - g\widetilde{c}(t). \quad (30)$$

8.1.3 Human Capital

The stock of skilled workers will coincide with those students who have completed their education and are still alive, born in $[t - D, t - Tr]$:

$$\widetilde{H}(t) = \tilde{\beta} \int_{t-D}^{t-Tr} N(s)(1 - \theta_0(s))ds = \tilde{\beta} N(t) \int_{t-D}^{t-Tr} e^{g(s-t)}(1 - \theta_0(s))ds \quad (3)$$

The total workforce (including students) in equilibrium equals total population, hence:

$$M(t) + \widetilde{H}(t) + C(t) = e^{gt}.$$

Due to heterogeneous learning abilities, in order to obtain the aggregate skilled labour supply, we need to multiply each skilled worker by the average amount of human capital that she can supply, given by the average skill of her cohort net of dispersion parameter Γ:

$$\int_{\theta_0(t)}^{1} (\theta - \Gamma) \frac{1}{1-\theta_0(t)} d\theta = \frac{1+\theta_0(t) - 2\Gamma}{2}.$$

Therefore the aggregate amount of skilled labour in efficiency units (skilled labor supply) is:

$$H(t) = \tilde{\beta} N(t) \int_{t-D}^{t-Tr} \frac{e^{g(s-t)}(1-\theta_0(s))\left(1+\theta_0(s)-2\Gamma\right)}{2} ds$$

Dividing by time t population, we can express percapita human capital as:

$$h(t) \equiv \frac{H(t)}{N(t)} = \frac{\tilde{\beta}}{2} \int_{t-D}^{t-Tr} e^{g(s-t)}(1-\theta_0(s))\left(1+\theta_0(s)-2\Gamma\right) ds. \tag{31}$$

The steady state value is:

$$h = \tilde{\beta} \frac{\left[e^{g(-Tr)} - e^{g(-D)}\right](1-\theta_0)(1+\theta_0-2\Gamma)}{2g} \tag{32}$$

The dynamics of human capital can be studied by derivating this expression with respect to time:

$$\begin{aligned} \dot{h}(t) &= -gh(t) + \frac{\tilde{\beta}}{2} e^{-gTr}(1-\theta_0(t-Tr))\left(1+\theta_0(t-Tr)-2\Gamma\right) - \\ &\quad + \frac{\tilde{\beta}}{2} e^{-gD}(1-\theta_0(t-D))\left(1+\theta_0(t-D)-2\Gamma\right). \end{aligned} \tag{33}$$

8.2 Transitional Properties of Educational Choice

The study of the transition dynamics of this model is complicated by the skilled/unskilled labour dynamics and by the endogenous population choice under perfect foresight. Key to the solution is the transformation of the integral equation for the ability threshold level for education into a set of differential equations.

Defining the present value of the unskilled wage incomes as $W_U(t) = \int_t^{t+D} e^{-\int_t^s i(\tau)d\tau} ds$ and the present value of the skilled wage income as $W_S(t) = \int_{t+Tr}^{t+D} e^{-\int_t^s i(\tau)d\tau} w_H(s)ds$, we know from (4) that

$$\theta_0(t) = \Gamma + \frac{W_U(t)}{W_S(t)}. \tag{34}$$

Defining

$$R_1(t) = e^{-\int_t^{t+D} i(\tau)d\tau}, \text{ and} \tag{35}$$

$$R_2(t) = e^{-\int_t^{t+Tr} i(\tau)d\tau} \tag{36}$$

we can write:

$$\dot{W}_U(t) = R_1(t) - 1 + i(t)W_U(t) \tag{37}$$

$$\dot{W}_S(t) = R_1(t)w_H(t+D) - R_2(t)w_H(t+Tr) + i(t)W_S(t). \tag{38}$$

Differentiating eq.s (35)-(36) with respect to time we obtain:

$$\dot{R}_1(t) = R_1(t)(i(t) - i(t+D)), \text{ and} \tag{39}$$

$$\dot{R}_2(t) = R_2(t)(i(t) - i(t+Tr)). \tag{40}$$

These equations allow us to cast our model in a framework that can be studied in terms of delayed differential equations.

8.3 Expenditure and Manufacturing Dynamics

From eq.s (10) follows:

$$\frac{\gamma - 1}{\gamma} E(t) = (\gamma - 1) \frac{1}{1-\alpha} m(t). \tag{41}$$

Log-differentiating with respect to time, using Euler equation (3) and the unskilled law of motion (27) yield:

$$i(t) - (\rho + g) = \frac{\dot{E}(t)}{E(t)} = \frac{\dot{m}(t)}{m(t)} = \frac{\tilde{\beta}\theta_0(t) - \tilde{\beta}e^{-gD}\theta_0(t-D)}{m(t)} - g \tag{42}$$

that - since $r(t) = i(t) - g$ - can be rewritten as

$$r(t) - \rho = \frac{\tilde{\beta}\theta_0(t) - \tilde{\beta}e^{-gD}\theta_0(t-D)}{m(t)} - g, \tag{43}$$

In the steady state: $r(t) = \rho$.

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