Ambiguity Attitude, R&D Investments and Economic Growth*

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Abstract

The process aimed at discovering new ideas is an economic activity whose returns are intrinsically uncertain. In a standard neo-Schumpeterian growth framework we assume that, when deciding upon R&D efforts, economic agents hold 'ambiguous beliefs' about the exact probability of arrival of the next vertical innovations, and face ambiguity via the $\alpha-$MEU decision rule (Ghirardato et al. (2004)). Along the steady-state equilibrium the higher the agents' ambiguity *aversion* (α), the lower the R&D efforts and, *coeteris paribus*, the overall economic performance. Consistently with a cross-country empirical evidence, this causal mechanism suggests that, together with the profitability conditions of the economy, different 'cultural' attitudes towards ambiguity may contribute to explain the different R&D intensities observed across countries.

Keywords: Schumpeterian growth, ambiguity, cultural attitude towards Ambiguity, arrival rate of innovation, R&D investments.

JEL Classification: 032, 041, D81, Z1.

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*The authors would like to thank the seminar participants at the European University Insitute and at the University of Rome "La Sapienza". Paolo Giordani thankfully acknowledges financial support from the Robert Schuman Centre for Advanced Studies (EUI).

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1 Introduction

Investment decisions in R&D are mostly taken under conditions of strong uncertainty (Knight, 1921) on their expected returns: Innovations are in fact unique events, and the process aimed at producing them is - both by logic and by historical inspection - an intrinsically uncertain economic activity. In the words of Nathan Rosenberg (1994, p. 93) "the essential feature of technological innovation is that it is an activity that is fraught with many uncertainties. This uncertainty, by which I mean an inability to predict the outcome of the search process, or to predetermine the most efficient path to some particular goal, has a very important implication: the activity cannot be planned". The importance of uncertainty in R&D decision-making is also largely confirmed by the empirical evidence on firm behavior[1]. If uncertainty pervades the decision setting for R&D investments, then the economic agents' *attitude* towards uncertainty is crucial to understand in more depth the nature and the characteristics of the innovation process.

Strong uncertainty plays no role in innovation-driven growth theory. The assumption of a perfectly assessable investment horizon - that is, the idea that transparent and well-organized financial markets allow savers to finance R&D activity in the light of an expected discounted value of future returns 'revealed' by an efficient stock market - is in fact standard along such models as Romer (1990), Aghion and Howitt (1992), Grossman and Helpman (1991) and subsequent developments. In particular, in Schumpeterian growth theory (SGT) the Schumpeter's view of economic development, as spurred by incessant R&D races aimed at gaining monopoly profits, is incorporated into an Arrow-Debreu dynamic general equilibrium framework with 'measurable uncertainty' (risk).

In SGT the arrival of innovation in the economy is usually formalized via a Poisson process. The parameter of this process, representing the 'flow probability' of innovation, is constant and perfectly known by R&D firms. In particular, in the original framework developed by Aghion and Howitt (1992), the value of this parameter (λ), affects both the problem of whether or not to invest in R&D (whose solution is embodied by the 'arbitrage equation'), and the problem of whether to invest in risk-free assets or in shares of monopolistic firms (whose solution is embodied by the 'asset equation').

In this framework we remove the assumption of a 'rigorously calculable future',

[1] See, among the others, Freeeman and Soete (1997), Chapter 10.

and provide a first attempt to formally introduce strong uncertainty (or, as we will see, *ambiguity*) in the process describing the evolution of innovation. In particular, we allow for the 'true' flow probability of innovation λ_t to change over time and consider the existence of investors holding 'ambiguous beliefs' about the exact value of that probability. We refound the basic Schumpeterian framework in the light of this new assumption, and consider the representative agent facing the two decision problems recalled above via the $\alpha-$MEU decision rule (Hurwicz (1951), Ghirardato et al. (2004)). In the steady-state equilibrium the amount of resources devoted to R&D, and hence the expected balanced growth path, crucially depend upon the way agents face the ambiguity in the arrival of innovation. In particular, the higher the ambiguity aversion of the representative agent (as measured by the coefficient α), the lower the equilibrium R&D efforts.

We propose a "cultural intepretation" of the causal mechanism - going from ambiguity attitude to R&D investments - highlighted in the paper. If we interpret the attitude towards uncertainty as a country-specific cutural trait - as Hofstede (2001) does, when building the uncertainty avoidance index for a number of countries (see next Section and the Appendix) -, our theoretical result suggests to expect that, *coeteris paribus*, countries where citizens show a high tolerence for ambiguity are more involved in innovative activity and viceversa. This is indeed what we find in the empirical evidence shown in Section 2.

This paper aims at extending a standard Schumpeterian framework in order to account for the lack of information characterizing the returns on R&D investments. On the one hand, in proving the robustness of this theoretical framework to the investors' strong uncertainty, it can be interpreted as an attempt to overcome the concern expressed by Rosenberg (1994, p. 93) - namely that "the activity cannot be planned" - through the theory of decision-making under ambiguity. On the other hand, and consistently with the empirical evidence shown in the next Section, the mechanism theoretically highlighted in it suggests that, together with the profitability conditions of the R&D sectors, different *cultural* attitudes towards uncertainty across countries may contribute to explain the differences in the R&D intensities observed among them.

The rest of the paper is organized as follows. In the next Section we show the empirical evidence on the relationship between a measure of tolerance towards uncertainty and R&D investments. In Section 3 we briefly recall the two concepts of ambiguity and ambiguity attitude. In Section 4 we provide a reminder of the simplest Schumpeterian framework, which we then use in Section 5 to determine the steady-state equilibrium

R&D efforts under ambiguity. In Section 6 we develop the welfare analysis.

2 Empirical Evidence

Consistently with the causal mechanism highlighted in the model we observe, across OECD countries, a negative correlation[2] between different measures of the innovative activity (R&D expenditure or number of researchers) and the 'uncertainty avoidance index' (UAI), which measures "the extent to which the members of a culture feel threatened by uncertain or unknown situations"[3] (Hofstede (2001)). Figures 1 and 2 show this correlation using respectively average R&D intensities or R&D researchers over the last ten years.

Shane (1993) has estimated the impact of different cultural values on the national rates of innovation across 33 countries. The cultural values he has considered are those developed by Hofstede (1980, 2001): uncertainty avoidance, power distance, masculinity and power distance; the national rate of innovation is measured by the number of trademarks. After controlling for the industrial structure and the GDP per capita across countries, Shane finds that the most (and always) significant explanatory variable is the uncertainty avoidance index: *coeteris paribus*, the lower the UAI the higher the number of trademarks issued by a country.

Another recent empirical contribution along these lines is Huang (2006), who shows that the different levels of tolerance towards ambiguity across countries, as measured by UAI, are responsible for the different growth rates that we observe in the most innovative industrial sectors of these countries: the empirical analysis suggests that these sectors, usually characterized by relatively more 'informational opacity' (that is, by more vague information about their returns), grow much more slowly (rapidly) in countries with relatively higher (lower) levels of UAI. This conclusion indirectly supports our claim that R&D employment, reasonably associated with the most innovative sectors of the economy, is negatively affected by ambiguity aversion.

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[2] Across European countries the negative correlation is even stronger.

[3] The UAI is a broad measure of the country-specific cultural attitude towards uncertainty, built by interviewing 88000 IBM employees across more than 70 countries. See the appendix for a detailed description of the index, and for the connection between this index and ambiguity aversion.

3 Ambiguity and Ambiguity Attitude

Ambiguity is to be intended in the sense that, given a typical uncertain choice scenario, the decision maker's (DM) information about feasible states of nature is too vague to be represented by a - single, additive - probability measure. *Ambiguity attitude* refers to the DM's reaction in the face of that ambiguity: that reaction can in fact be of either aversion or attraction (and, of course, of different degrees of either of them) to the ambiguity the DM perceives.

Ellsberg (1961) was the first one to show, through a mind experiment (known as the Ellsberg Paradox[4]), the incompatibility between a 'reasonable' and widespread choice in his experiment and the one dictated by the SEU principle (Savage (1954)), which represents the standard treatment of decision making under uncertainty in economics. The paradox emphasizes that people tend to make a distinction between clear (objective) probabilities and vague (subjective) probabilities, an argument which reminds of the old Keynesian distinction between 'probability' and 'weight of evidence'[5] (Keynes (1921)). Schmeidler (1989) and Gilboa and Schmeidler (1989) gave a first axiomatic formalization to the idea of ambiguity via respectively two different extensions of the SEU theory: the first, called CEU (Choquet expected utility), basically replaces the additive probability measure with a non-additive one (a *capacity*) and computes the expected utility through the Choquet integral; the second, called MEU (maxmin expected utility), replaces the single (additive) prior with *multiple* (additive) priors and computes expected utlility on the basis of the worst prior.

Although CEU and MEU have given an operational meaning to the concepts of ambiguity and ambiguity attitude, they have encountered problems in providing a clear distinction between them. One way to (partially) overcome these problems has been recently taken in a multiple-prior setting by Ghirardato et al. (2004)[6]. In particular, we follow a special case axiomatized in it called $\alpha-MEU$ decision rule. This rule is

[4] The two-urn version of the experiment goes as follows: two urns are given, each of which contains ten balls, whose color is either white or black. One of them is known to contain five white balls and five black balls, while no information is given on the distribution of the balls' colors in the other urn. The decision maker is asked to bet on the color of the first ball drawn at random from either urn, and must decide which urn she prefers. The paradox arises whenever people show a preference for the 'known' urn, that is, for the urn containing five white and five black balls. This choice behavior cannot be explained by the subjective expected utility (SEU) principle, since there is no subjective (additive) probability distribution that supports these preferences.

[5] The 'probability' represents the balance of evidence in favor of a particular proposition, while the 'weight of evidence' stands for the quantity of information supporting that balance.

[6] For a discussion of the limits of this approach see Klibanoff, Marinacci and Mukerji (2005).

an extension of the Hurwicz's (1951) $\alpha-$pessimism index criterion, which computes a $\alpha-$weighted sum (for $\alpha \in [0,1]$) of the maxmin expected utility (obtained via the selection of the worst prior) and the maxmax expected utility (obtained via the selection of the best prior). In the $\alpha-$MEU the ambiguity perceived by the DM is measured by the extension of priors, while the ambiguity aversion is (positively) measured by the coefficient α (the higher it is, the higher is the weight associated with the worst case). The MEU is of course a particular case of the $\alpha-$MEU in which $\alpha = 1$ (that is, in which ambiguity aversion is at its maximum). Given a utility function u, a set of priors Π and a state space S with $s \in S$, the evaluation of act f is made according to the following functional:

$$I_f = \alpha \min_{p \in \Pi} \int_S u(f(s))dp(s) + (1-\alpha) \max_{p \in \Pi} \int_S u(f(s))dp(s).$$

4 The neo-Schumpeterian Framework

We now briefly recall the basic framework developed in Aghion and Howitt (1992). Time is continuous and there exists a continuum of infinitely lived households with identical intertemporally additive preferences, with r representing the rate of time preference. Since instantaneous utility is assumed to be linear and there are perfect capital markets, then r also turns out to be the equilibrium interest rate. Households are endowed with flow units of skilled or unskilled labor time and are assumed to supply them inelastically in a perfectly competitive market.

There is a perfectly competitive final sector, in which output is produced according to a constant returns to scale (CRS) technology. For simplicity, we assume a Cobb-Douglas specification:

$$y_t = A_t x_t^{\theta} N_t^{1-\theta} = A_t x_t^{\theta} \qquad 0 < \theta < 1$$

where y is final output, x is the intermediate good and N, normalized to 1, is the unskilled labor. A is the productivity parameter, which is assumed to evolve according to the following rule:

$$A_{t+1} = \gamma A_t \text{ for } \gamma > 1 \text{ and } t = 0, 1, 2...$$

The subscript t does not refer to calendar time (indexed by τ) but to the generation of the intermediate product that is being used. Whenever a new intermediate product is introduced into the market, the economy jumps by γ. The intermediate good x is produced through a one-to-one technology from skilled labor (L). The final output is assumed to be the numerarie: $p(y_t) = 1$.

Before describing the innovation process, let us illustrate what happens when a new quality is discovered: as soon as a new intermediate product is introduced, it is automatically protected by a perfect and infinitely lived patent, which allows the inventor (or whoever buys the blueprint) to temporarily monopolize the market. With the assumption that innovations are drastic, monopoly profits can be easily obtained from the profit maximizing condition:

$$\max_{x_t} \left[\pi_t = A_t \theta x_t^{\theta-1} x_t - x_t w_t \right],$$

where w_t is the skilled labor wage. This maximization gives the optimal value of x_t as

$$x_t = \left(\frac{w_t}{A_t \theta^2} \right)^{\frac{1}{1-\theta}}.$$

Maximum profits can then be written as

$$\pi_t = \frac{1-\theta}{\theta} x_t w_t. \tag{1}$$

The innovation process takes place because R&D firms employ, in a perfectly competitive market, an amount n of skilled labor in order to gain a probability of discovering the next vintage. Since skilled labor can switch from the research sector to the intermediate sector and viceversa, the skilled labor market clearing condition can be written as

$$L = x_t + n_t,$$

where x_t and n_t represent labor employed respectively in the intermediate and the research sectors. We also define V_t as the market value of the monopolistic firm producing vintage t.

According to the standard Schumpeterian literature, the arrival of innovation in the economy is assumed to follow a Poisson Process. The parameter λ of this process, representing the flow probability of an innovation, is constant and known by the investor. Because of CRS in the research sector, the number of R&D firms is indeterminate. In equilibrium expected benefits from a unit of R&D effort (λV_{t+1}) must equal its cost

(w_t). The equation

$$\lambda V_{t+1} = w_t \tag{2}$$

is usually called the 'research arbitrage equation' of the model. Furthermore, because instantaneous utilities are linear, agents must be indifferent between investing in shares of the incumbents and investing in risk-free assets. Then the value V_{t+1} must satisfy the following 'asset equation':

$$rV_{t+1} = \pi_{t+1} - \lambda n_{t+1} V_{t+1},$$

where rV_{t+1} is the return from investing in risk-free shares, π_{t+1} is the flow of profits corresponding to vintage $t+1$, while $\lambda n_{t+1} V_{t+1}$ is the expected capital loss due to the introduction of vintage $t+2$, and embodies the Schumpeter's 'creative destruction effect' associated with innovation. The asset equation gives the expression for V_{t+1} as

$$V_{t+1} = \frac{\pi_{t+1}}{r + \lambda n_{t+1}}, \tag{3}$$

stating that the market value of the monopolistic firm producing vintage $t+1$ is the flow of profits that it will produce, discounted at the obsolescence-adjusted interest rate[7]. We are now ready to modify this basic set-up so as to incorporate the agents' ignorance about the arrival rate of innovation.

5 Equilibrium R&D Efforts under Ambiguity

For each vintage t agents hold 'ambiguous beliefs' about the true 'flow probability of innovation' λ_t. We assume that, for each t, investors believe that λ takes a strictly positive finite value, that is to say: $\lambda_t \in [m, M]\ \forall t$ where $m, M \in \,]0, +\infty[$ and $M > m$[8]. The width of the interval - e.g., the extension of priors - is a measure of the ambiguity perceived by the agents. Furthermore, in our setting agents have no possibility of im-

[7] Notice that the λ appearing in (2) and the one appearing in (3) are ldistinct, since they refer to the productivity of R&D in discovering respectively vintages $t+1$ and $t+2$. It follows that the structure of this class of models imposes that, when deciding upon R&D activity in t, investors know the exact probabilities (λ) of the next *two* vertical innovations. Of course in the standard model this is easily satisifed because λ is assumed constant.

[8] This assumption is meant to exclude the uninteresting cases in which the agent is either totally hopeless about the possibility of innovating ($\lambda_t = 0$), or absolutely sure of producing an innovation in the exact instant in which he invests ($\lambda_t \to +\infty$).

proving their knowledge upon the parameter via a 'learning process', since innovations are unique events - the probability distribution changes from an innovation to another - and, hence, there is no statistical basis for embarking on calculations.

In the light of this assumption on the agents' beliefs, two decision problems stated in Section 4 must be reconsidered. The former is the problem of whether or not to devote investments to R&D and the latter is the problem of whether to invest in shares of the incumbents or in risk-free assets. We will study them in order under the decision rule introduced in Section 3.

5.1 Problem 1 (The Research Arbitrage Equation)

Assume that the economy is in t (that is, assume that generation t of the intermediate good is being produced). Under ambiguous beliefs about the value taken by λ_t (which, notice, represents the probability of discovering vintage $t+1$), the R&D firm has to decide whether or not to hire workers in R&D by comparing the profitability associated with these two alternatives. If the firm does not hire any R&D worker, its return will always be null, independently of the true value of λ_t. If it does, the cost of each R&D investment unit is the skilled labor wage (w_t), while expected benefits ($\lambda_t V_{t+1}$) depend on the strictly uncertain probability $\lambda_t \in [m, M]$: the return from R&D investment will then be $\lambda_t V_{t+1} - w_t$ for $\lambda_t \in [m, M]$.

Given this decision problem, the DM - R&D firm - adopting the $\alpha-$MEU decision rule evaluates her expected returns from R&D by computing a α-weighted average of the maxmin level (also called 'security level', $mV_{t+1} - w_t$) and the maxmax level (also called 'optimism level', $MV_{t+1} - w_t$), that is, $[\alpha m + (1-\alpha)M]\, V_{t+1} - w_t$, where $0 \leq \alpha \leq 1$ is a parameter measuring the aversion to ambiguity. By comparing this pay-off with the null pay-off associated with 'no R&D investment', indifference as to whether or not to invest in R&D can then be expressed via the following arbitrage equation[9]:

$$w_t = \alpha m V_{t+1} + (1-\alpha) M V_{t+1}. \tag{4}$$

[9] A particular case of the one above is the Gilboa-Schmeidler's (1989) maxmin criterion, in which the DM fears that a 'malevolent nature' is selecting the worst prior inside the set $[m, M]$. The arbitrage equation is trivially obtained from (4) by imposing $\alpha = 1$.

5.2 Problem 2 (The Market Value of Incumbents)

What is the market value of the monopolistic firm producing generation $t+1$ of the intermediate good (V_{t+1})? In order to derive its expression, we need to address the agent's problem (in $t+1$) of whether to invest in risk-free assets or in shares of current monopolists in the light of the strict uncertainty associated with the parameter λ_{t+1}. There are two possible acts, investing in risk-free assets or in shares of the monopolistic firms: if the investor decides to buy risk-free assets, her return will always be rV_{t+1}, independently of the productivity of the research technology. On the other hand, if she invests in shares of the incumbents, then her pay-off will be $\pi_{t+1} - \lambda_{t+1} n_{t+1} V_{t+1}$, where now λ_{t+1} represents the productivity of the R&D aimed at discovering vintage $t+2$: the risky asset return is then a decreasing function of λ_{t+1}.

For an $\alpha-$MEU decision maker the return associated with investing in shares is given by the α-weighted average of the maxmin level ($\pi_{t+1} - Mn_{t+1}V_{t+1}$) and the maxmax level[10] ($\pi_{t+1} - mn_{t+1}V_{t+1}$), while the one corresponding to investing in risk-free assets is always rV_{t+1}. Indifference as to whether to invest in shares or in risk-free assets is reached when these values equalize[11]. Then in equilibrium it must be $rV_{t+1} = \pi_{t+1} - [\alpha M + (1-\alpha)m]n_{t+1}V_{t+1}$ and hence[12]

$$V_{t+1} = \frac{\pi_{t+1}}{r + [\alpha M + (1-\alpha)m]n_{t+1}}. \tag{5}$$

5.3 The Steady-State Equilibrium

In steady-state the monopolistic profits in $t+1$ are

$$\pi_{t+1} = \gamma \pi_t = \gamma \frac{1-\theta}{\theta} x_t w_t.$$

By substituting that value into (5) and (5) into (4) we easily obtain the final expression for the arbitrage equation, which, together with the labor market-clearing condition, form the system describing the evolution of this economy:

[10] Notice that, as opposed to problem 1, now m and M are respectively associated with the maxmax level and the maxmin level.

[11] Remember that, by assumption, the DM is risk neutral.

[12] Once again, the maxmin solution (in the sense of Gilboa and Schmeidler (1989)) is obtained from (5) by simply imposing $\alpha = 1$.

$$
\begin{cases}
w_t = [\alpha m + (1-\alpha)M] \dfrac{\gamma^{\frac{1-\theta}{\theta}} x_t w_t}{r + [\alpha M + (1-\alpha)m] n_{t+1}} \\
L = x_t + n_t.
\end{cases}
$$

By imposing $n_t = n_{t+1}$, we can rewrite this system as

$$
\begin{cases}
1 = [\alpha m + (1-\alpha)M] \dfrac{\gamma^{\frac{1-\theta}{\theta}} x}{r + [\alpha M + (1-\alpha)m] n} \\
L = x + n.
\end{cases}
\tag{6}
$$

from which we can easily determine the equilibrium value of the research effort[13]

$$
n^*_\alpha = \frac{[\alpha m + (1-\alpha)M]\gamma^{\frac{1-\theta}{\theta}} L - r}{[\alpha M + (1-\alpha)m] + \gamma[\alpha m + (1-\alpha)M]^{\frac{1-\theta}{\theta}}}.
\tag{7}
$$

It is easy to prove that $\dfrac{\partial n^*_\alpha}{\partial \alpha} < 0$, which means that *the mass of workers employed in R&D is a decreasing function of their ambiguity aversion*. The average expected growth rate in steady-state is given by the expected number of innovations per unit of time multiplied by the size of the step ahead brought about by each of them. It will then be: $g^*_\alpha = [\alpha M + (1-\alpha)m] n^*_\alpha \ln \gamma$. Perhaps more interestingly, the observed growth rate of an economy in steady-state depends on the number of innovations *actually* occurred - which in turn depend on the values taken by the true parameter λ_τ and on the R&D employment. In principle, it is then all but difficult to immagine two economies, one of which experiencing constantly higher λ_τ over time and still growing at a slower rate, only as a result of a more conservative attitude towards uncertainty of the agents.

While comparative statics analysis for γ, L, θ and r is in line with the original Schumpeterian model[14], the relation between the arrival rate of innovation and the equilibrium R&D efforts deserves attention. In the original Schumpeterian model the research efforts n^* are a positive function of λ[15]. Equally, here research efforts are a positive function of the estimation of the unknown arrival rate λ. However, the effect

[13] The research efforts under pure maxmin strategy are obtained from (7) by setting $\alpha = 1$.

[14] Both a higher quality jump γ and a larger amount of skilled labor force L raise the equilibrium R&D effort n^*_α, while a higher rate of interest r, and a higher value of θ (inversely measuring the degree of market power) lower it.

[15] More precisely, we must distinguish between two conflicting effects. On the one hand, an increase in the arrival rate makes the research activity more productive for a given level of employment, thus stimulating the R&D effort. On the other hand, this increase exacerbates the creative destruction effect, reducing the R&D effort. The former effect, however, dominates the latter.

on n^* of an increase in ambiguity with which λ is perceived, that is, of an increase in the extension of priors $[m, M]$ over λ is itself 'ambiguous': it can be positive or negative depending on the *attitude* towards ambiguity: it may well happen that an increase in ambiguity raises the R&D intensity when individuals are relatively ambiguity seeking. The effect of the ambiguity *attitude* has instead already been recalled above: an increase in ambiguity aversion has a negative impact on R&D efforts ($\partial n^*_\alpha / \partial \alpha < 0$), which means that an economy with a scarse tolerance of ambiguity will invest relatively little in R&D and, given the key-role of R&D for economic growth, will *coeteris paribus* lag behind another economy with a more positive attitude towards ambiguity.

6 Welfare Analysis

In this Section we compare the laissez-faire equilibrium R&D effort n^*_α with the one chosen by a social planner seeking to maximize the welfare of the representative agent n^{sp}_α. Such welfare, called U_t, is the valuation, based on the risk-free rate of time preference r, of the consumption available at all future dates. The reasoning underlying the derivation of U_t closely resembles the one carried out to derive V_t in (3), with two important differences: first, as the reader recalls from Section 3 where we determined the market value of the monopolistic firm, the shareholders are only interested in the flow of profits (π_t); in contrast, here consumers care about the current expected value of their entire consumption prospect (given by the final product y_t, as a sum of both wages and profits). U_t can actually be interpreted as the value of an asset which gives to the owner the right to receive, as a return, the whole national income. Second, in deriving (3) we saw that the arrival of the next innovation exercises a negative effect on the market value of the incumbent (because of its 'creative destruction' effect). Conversely, from a social perspective the arrival of the successive innovation enhances unambiguously the consumers' welfare, which jumps to $U_{t+1} = \gamma U_t$, with a net collective gain equal to $U_{t+1} - U_t = (\gamma - 1)U_t$. This social gain occurs with probability λn in the unit of time, and its expected value is then $\lambda n(U_{t+1} - U_t)$. As a result, the overall return from this 'asset' is $y_t + \lambda n(U_{t+1} - U_t)$, which must be equal to that obtained under the rate r, that is

$$rU_t = y_t + \lambda n(U_{t+1} - U_t). \tag{8}$$

The social planner, however, holds ambiguous beliefs about the true value of the arrival rate of innovation λ. Under the $\alpha-$MEU decision rule, and by following an argument in all respects analogous to the one elaborated for the case of laissez-faire, equilibrium condition (8) simply becomes

$$y_t + [\alpha m + (1-\alpha)M]n(U_{t+1} - U_t)] = rU_t.$$

Once substituting for $y_t = A_t(L-n)^\theta$ and $U_{t+1} = \gamma U_t$, the condition above can be solved for U_t and gives

$$U_t = \frac{A_t(L-n)^\theta}{r - [\alpha m + (1-\alpha)M]n(\gamma - 1)}.$$

By maximizing U_t with respect to n, we find the socially optimal research effort:

$$n_\alpha^{sp} = \frac{[\alpha m + (1-\alpha)M](\gamma-1)\frac{1}{\theta}L - r}{[\alpha m + (1-\alpha)M](\gamma-1)\frac{1-\theta}{\theta}}.$$

The comparison between the optimal laissez-faire research effort and the socially optimal one (that is, n_α^* vs. n_α^{sp}) reveals that, as in Aghion-Howitt (1992), the former value can be higher or lower than the latter, and exactly for the same reason. The 'intertemporal spillover effect' and the 'appropriability effect' tend to make the laissez-faire value lower than the socially optimal one, while the 'business stealing effect' operates in the opposite direction: as a result, whether there is under-investment or over-investment in R&D ultimately depends on the specific values of the parameters involved.

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A The Uncertainty Avoidance Index

The UAI has been computed for 72 countries, by interviewing 88000 IBM employees, from 1967 to 1973 and asking the three following questions:

1. *Rule orientation*: agreement with the statement "Company rules should not be broken, even when the employee thinks it is in the company's best interest" (5-point answer scale, from strongly agree to strongly disagree: the more rule-oriented, the more uncertainty-avoiding).

2. *Employment stability*: employees' statement that they intend to continue with the company (1) for 2 years at most (2) from 2 to 5 years (3) more than 5 years (but before retiring) (4) until they retire (the more stability-seeking, the more uncertainty-avoiding).

3. *Stress*, as expressed in the mean answer to the question "How often do you feel nervous or tense at work?" (5-point answer scale from 'I always feel this way' to 'I never feel this way': the more stressed, the more uncertainty-avoiding).

The number is computed on the basis of the country mean scores for the answers given to the questions above, and the exact formula is the following:

$$
\begin{aligned}
UAI &= 300 - 30 \times (\text{mean score rule orientation, from 1 to 5}) + \\
&\quad -(\text{percentage intending to stay less than 5 years, from 0 to 100}) + \\
&\quad -40 \times (\text{mean stress score, again from 1 to 5}).
\end{aligned}
$$

The index ranges from a minimum of -150 to a maximum of of $+230$. This kind of experiment has been replicated over time - even using different populations, and slightly different questions as a consequence - and the results on UAI have always been basically confirmed (to prove the persistence over time of 'cultural values').

The link between the UAI and the $\alpha-$MEU decision rule is intuitively strong: the UAI can roughly be considered as a proxy of the parameter α across countries, in measuring their different degree of tolerance towards ambiguity. Although intuitively sound, this relationship is admittedly problematic in one respect which is worth remarking: while our theoretical formalization can easily distinguish between ambiguity (that is, the structural uncertainty of the decision setting measured by the width of the interval $[m, M]$) and attitude towards ambiguity (measured by the coefficient α), the UAI does not: to give a simple example, the agent's answer to the 'employment stability' question is probably dictated by both her personal taste for ambiguity and the labor market conditions of her country. With this *caveat* in mind, the fact remains true that the causal mechanism highlighted in the model, according to which a fall in the ambiguity aversion index α leads to an increase in R&D employment n, is well in accord with the negative correlations between UAI and different measures of the R&D activity shown in figures 1-3.

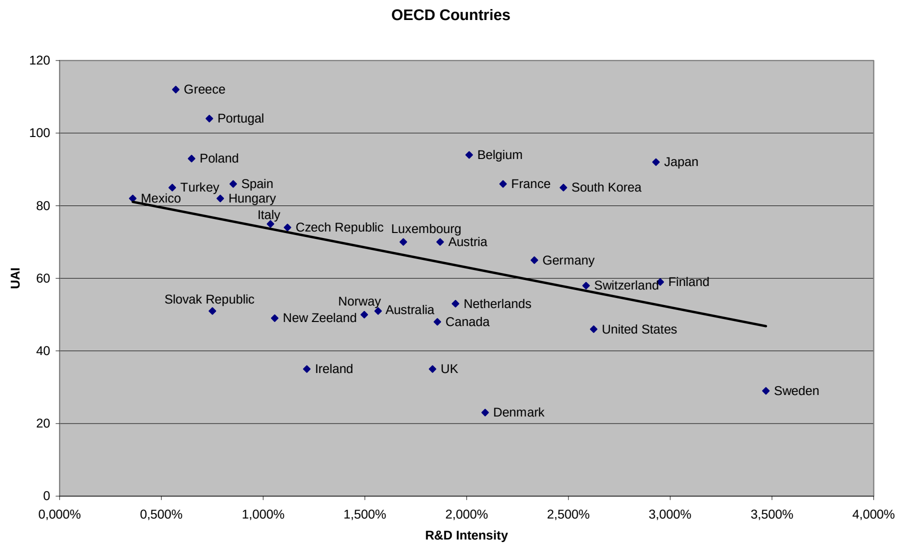

Figure 1: Source OECD

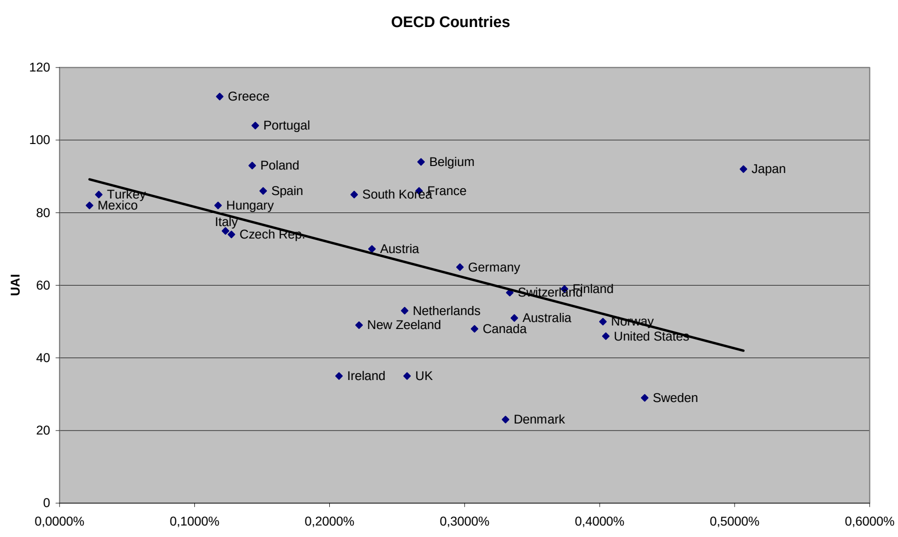

Figure 2: Source UN