

# 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 innovation, and face ambiguity via the  $\alpha$ -MEU decision rule (Ghirardato et al. (2004)). Along the steady-state equilibrium, the higher the agents’ ambiguity *aversion* ( $\alpha$ ), the lower the R&D efforts and, *coeteris paribus*, the overall economic performance. Consistent with cross-country empirical evidence, this causal mechanism suggests that, together with the profitability conditions of the economy, different ‘cultural’ attitudes towards ambiguity may help explain the different R&D efforts observed across countries.

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

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# 1 Introduction

Investment decisions in R&D are mostly taken under conditions of strong uncertainty on their expected returns (Knight, 1921). Innovations are 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 empirical evidence on firm behavior.<sup>1</sup> If uncertainty pervades the decision setting for R&D investments, then the economic agents’ *attitude* towards uncertainty is crucial to fully understand 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 standard in such models as Romer (1990), Aghion and Howitt (1992), Grossman and Helpman (1991) and subsequent developments. In particular, in Schumpeterian growth theory (SGT), 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, usually denoted by  $\lambda$  and representing the flow probability of innovation per unit of investment in R&D, is constant and known by R&D firms. This parameter affects the profitability conditions of R&D investments. In particular, in the original framework developed by Aghion and Howitt (1992), it affects both the problem of whether or not to invest in R&D (whose solution is embodied by the ‘research 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 theoretical framework we remove the assumption of ‘rigorously calculable

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<sup>1</sup>See, among others, Freeman and Soete (1997), Chapter 10.

future’, 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’ value of  $\lambda$  to change over time and consider the existence of investors holding ‘ambiguous beliefs’ about its exact value. We refound the basic Schumpeterian framework under 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 coefficient  $\alpha$ ), the lower the equilibrium R&D efforts, and the slower the innovative process in the economy.

We propose a cultural interpretation 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 cultural trait - as Hofstede (2001) does, when building the uncertainty avoidance index for a number of countries (see Section 2 and the appendix) - our theoretical result suggests that, *coeteris paribus*, countries where citizens show a high tolerance for ambiguity are more involved in innovative activity and viceversa. This is indeed what we find in the empirical evidence reviewed in Section 2.

In our model economic agents respond to the genuine uncertainty pervading the innovative process by adopting a simple, regular behavior, which incorporates their attitude towards ambiguity ( $\alpha$ ). In this respect our modeling approach is closely related to the literature on ‘organizational routines’ (Nelson and Winter, 1982) and, in particular, to those contributions emphasizing the link between environmental uncertainty and the emergence of routinized behavior.<sup>2</sup> When facing turbulent environments, economic agents tend to develop simple, *persistent* rules of collective behavior to cope with strong uncertainty. In the words of Heiner (1983, p. 570) “*greater uncertainty will cause rule-governed behavior to exhibit increasingly predictable regularities, so that uncertainty becomes the basic source of predictable behavior*” (italics in original). This is what happens in our framework, where a ‘routinized’ R&D investment behavior is induced by the non-stationarity of the innovative process. In particular, routines

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<sup>2</sup>See, among others, Dosi and Egidi (1991). Empirical works on the link between uncertainty and routines include Becker and Knudsen (2004), and Egidi (1996). For a relatively recent review of the literature on organizational routines see Becker (2004).

are influenced by parameter  $\alpha$ : in the face of a complex and changing environment, a relatively high  $\alpha$  (ambiguity aversion) embodies a cautious evaluation of profitable opportunities of investment, and gives rise to a persistently low R&D-effort behavior, and viceversa. As a result, countries where citizens show a low tolerance for ambiguity develop more innovation-averse investment routines and viceversa.

This work 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, this paper 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 consistent with the empirical evidence of the next section, our theoretical result suggests that, together with the profitability conditions of the R&D sector, different *cultural* attitudes towards uncertainty across countries may help explain the differences in the R&D investments observed among them.

The rest of the paper is organized as follows. In the next section we show some 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 carry out the welfare analysis.

## 2 Empirical Evidence

Consistent with the causal mechanism highlighted in the model we observe, across OECD countries, a negative correlation between different measures of innovative activity and the 'uncertainty avoidance index' (UAI), which measures "the extent to which the members of a culture feel threatened by uncertain or unknown situations" (Hofstede, 2001).<sup>3</sup> Figures 1 and 2 show this correlation using, respectively, average R&D intensities (that is, R&D expenditure over GDP), and average percentage of researchers over total population for period 1995-2004.<sup>4</sup>

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<sup>3</sup>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.

<sup>4</sup>Across European countries the negative correlation is even stronger.

INSERT FIGURES 1,2 HERE

Shane (1993) estimates the impact of different cultural values on the national rates of innovation across 33 countries. The cultural values he considers are those developed by Hofstede (1980, 2001): uncertainty avoidance, power distance, masculinity and individualism. 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 (2008), 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. Empirical analysis suggests that these sectors, usually characterized by relatively more ‘informational opacity’ (that is, by vaguer information about economic returns), grow much more slowly (rapidly) in countries with relatively higher (lower) levels of UAI. This conclusion indirectly supports our claim that R&D efforts, reasonably associated with the most innovative sectors of the economy, are negatively affected by 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), the incompatibility between a ‘reasonable’ and widespread choice in his experiment and the one dictated by the subjective expected utility (SEU) principle (Savage, 1954), representing the standard treatment of decision making under uncertainty in economics.<sup>5</sup> The paradox emphasizes that people tend to make a dis-

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<sup>5</sup>The two-urn version of the experiment goes as follows: there are two urns, each of which contains

inction between clear (objective) probabilities and vague (subjective) probabilities, an argument which reminds of the old Keynesian distinction between ‘probability’ and ‘weight of evidence’ (Keynes, 1921).<sup>6</sup> 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 Choquet expected utility (CEU), 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 maxmin expected utility (MEU), replaces the single (additive) prior with *multiple* (additive) priors and computes expected utility on the basis of the worst prior.

Although CEU and MEU principles 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 possible solution to these problems has been recently proposed in a multiple-prior setting by Ghirardato et al. (2004).<sup>7</sup> In particular, we follow a special case axiomatized in that paper, called  $\alpha$ -MEU decision rule. This rule is 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 rule, the ambiguity perceived by the DM is measured by the extension of priors, while ambiguity aversion is (positively) measured by parameter  $\alpha$ . The higher it is, the higher is the weight associated with the worst case. MEU is of course a particular case of  $\alpha$ -MEU in which  $\alpha = 1$ , that is, in which ambiguity aversion is at its maximum. Given a utility function  $u$ , a set of priors  $\Pi$  and a state space  $S$  with  $s \in S$ , the evaluation of act  $f$  is made according to the following functional:

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

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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 SEU principle, since there is no subjective (additive) probability distribution that supports these preferences.

<sup>6</sup>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.

<sup>7</sup>For a discussion of the limits of this approach see Klibanoff, Marinacci and Mukerji (2005).

## 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 linear and there are perfect capital markets,  $r$  is also 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:

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

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

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

The subscript  $t$  does not refer to calendar time (indexed by  $\tau$ ) 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  $\gamma$ . The intermediate good  $x$  is produced through a one-to-one technology from skilled labor ( $L$ ). The final output is assumed to be numeraire:  $p(y_t) = 1$ .

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. Under the assumption that innovations are drastic, monopoly profits can be easily obtained from the profit maximizing condition:

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

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

$$\pi_t = \frac{1-\theta}{\theta} x_t w_t. \quad (1)$$

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 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 with arrival rate given by  $\lambda n_t$ . The parameter  $\lambda$  of this process is the probability of discovering the next vintage per unit of labor employed in R&D, and hence represents the researchers' productivity. This parameter 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 ( $\lambda V_{t+1}$ ) must equal its cost ( $w_t$ ). The equation

$$\lambda V_{t+1} = w_t \quad (2)$$

is usually called the 'research arbitrage equation' of the model. Furthermore, because instantaneous utilities are linear, agents must be indifferent between investing in incumbents' shares and investing in risk-free assets. The value  $V_{t+1}$  must then 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 assets,  $\pi_{t+1}$  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

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

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.<sup>8</sup> We are now ready to modify this basic set-up so as to incorporate the idea that the probability of innovation is time-varying and unknown.

## 5 Equilibrium R&D Efforts under Ambiguity

For each vintage  $t$  agents hold ambiguous beliefs about the true probability of innovation per unit of labor employed in R&D,  $\lambda_t$ . We assume that, for each  $t$ , investors know that  $\lambda$  takes a strictly positive finite value, that is to say:  $\lambda_t \in [m, M] \forall t$  where  $m, M \in ]0, +\infty[$  and  $M > m$ .<sup>9</sup> 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 improving their knowledge upon the arrival of innovations via a ‘learning process’: given that innovations are unique events - the probability distribution changes from one innovation to another - there is no statistical basis for embarking on calculations.

In 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 resources to R&D, 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.

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<sup>8</sup>Notice that the  $\lambda$  appearing in (2) and the one appearing in (3) are distinct, 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 the condition that, when deciding upon R&D activity in  $t$ , investors know the exact probabilities of the next *two* vertical innovations. Of course, in the standard model this is easily satisfied because  $\lambda$  is assumed constant.

<sup>9</sup>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 at the exact instant she invests ( $\lambda_t \rightarrow +\infty$ ).

## 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  $\lambda_t$  (which, notice, represents R&D productivity for vintage  $t + 1$ ), the R&D firm has to decide whether or not to hire researchers. If it does not, its return will always be null, independently of the true value of  $\lambda_t$ . 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 R&D productivity,  $\lambda_t \in [m, M]$ : the return from R&D investment will then be  $\lambda_t V_{t+1} - w_t$  for  $\lambda_t \in [m, M]$ .

The firm's ignorance about  $\lambda_t$  leads it to apply a simple decision rule, which incorporates its attitude towards ambiguity ( $\alpha$ ). In particular, a firm adopting the  $\alpha$ -MEU decision rule evaluates its expected returns from R&D by computing an  $\alpha$ -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 the 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:<sup>10</sup>

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

## 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 light of the strict uncertainty associated with the probability of innovation per unit of R&D labor,  $\lambda_{t+1}$ . 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 true 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  $\lambda_{t+1}$  represents the productivity of

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<sup>10</sup>A particular case of the one above is the Gilboa-Schmeidler's (1989) MEU 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  $\alpha = 1$ .

R&D aimed at discovering vintage  $t + 2$ . The risky asset return is then a decreasing function of  $\lambda_{t+1}$ .

For an  $\alpha$ -MEU decision maker the return associated with investing in incumbents' shares is given by the  $\alpha$ -weighted average of the maxmin level  $(\pi_{t+1} - Mn_{t+1}V_{t+1})$  and the maxmax level  $(\pi_{t+1} - mn_{t+1}V_{t+1})$ ,<sup>11</sup> while the one corresponding to investing in risk-free assets is still  $rV_{t+1}$ . Indifference as to whether to invest in shares or in risk-free assets is reached when these values equalize. In equilibrium it must be

$$rV_{t+1} = \pi_{t+1} - [\alpha M + (1 - \alpha)m]n_{t+1}V_{t+1}$$

and hence<sup>12</sup>

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

### 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:

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

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

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

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<sup>11</sup>Notice that, as opposed to problem 1, now  $m$  and  $M$  are respectively associated with the maxmax level and the maxmin level.

<sup>12</sup>Once again, the MEU solution (in the sense of Gilboa and Schmeidler (1989)) is obtained from (5) by simply imposing  $\alpha = 1$ .

from which we can easily determine the equilibrium value of research efforts as<sup>13</sup>

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

It is easy to prove that  $\partial n_\alpha^*/\partial \alpha < 0$ , 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* realized - which in turn depend on the values taken by the true productivity  $\lambda_t$  over time and on the R&D employment  $n_\alpha^*$ . In principle, it is then all but impossible to imagine two economies, one of which is experiencing constantly higher  $\lambda_t$  over time and still growing at a slower rate, only as a result of an agents' more conservative attitude towards uncertainty ( $\alpha$ ).

Uncertainty attitude affects not only the average growth performance of the economy but also its volatility. If  $[\alpha m + (1 - \alpha)M]n_\alpha^*$  is the equilibrium expected arrival rate, the interarrival time of innovations is expected to be distributed exponentially, with mean and variance respectively given by  $1/[\alpha m + (1 - \alpha)M]n_\alpha^*$  and  $1/\{[\alpha m + (1 - \alpha)M]n_\alpha^*\}^2$ . As a result, an increase in ambiguity aversion (higher  $\alpha$ ) raises variance both directly -via  $[\alpha m + (1 - \alpha)M]$ - and indirectly -via a decrease in  $n_\alpha^*$ . The implication is that, whatever the true  $\lambda$  turns out to be at any point in time, a gloomier perception of the opportunities for innovative investment brings about an increase in the 'objective' uncertainty in the arrival times of innovations (via a lower  $n_\alpha^*$ ).

While comparative statics analysis for  $\gamma$ ,  $L$ ,  $\theta$  and  $r$  is in line with the original Schumpeterian model,<sup>14</sup> the relation between R&D productivity and equilibrium R&D efforts deserves attention. In the original Schumpeterian model research efforts  $n^*$  are a positive function of  $\lambda$ .<sup>15</sup> Equally, here research efforts are a positive function of

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<sup>13</sup>Research efforts under pure maxmin strategy (MEU criterion) are obtained from (7) by setting  $\alpha = 1$ .

<sup>14</sup>Both a higher quality jump  $\gamma$  and a larger amount of skilled labor force  $L$  raise the equilibrium R&D effort  $n_\alpha^*$ , while a higher rate of interest  $r$ , and a higher value of  $\theta$  (inversely measuring the degree of market power) lower it.

<sup>15</sup>More precisely, we must distinguish between two conflicting effects. On the one hand, an increase in  $\lambda$  makes the research activity more productive for a given level of employment, thus stimulating

the estimate of unknown  $\lambda_t$ . However, the effect on  $n_\alpha^*$  of an increase in ambiguity with which  $\lambda$  is perceived, that is, of an increase in the extension of priors  $[m, M]$  over  $\lambda$  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 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 little 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.

The link with the literature on ‘organizational routines’, which we stressed in the Introduction, can now be fully appreciated. The productivity of R&D technology ( $\lambda_t$ ) is time-varying and unknown to economic agents. The estimate of this productivity is crucial for determining agents’ behavior, in that it affects both the probability of the next innovation and its value. In the face of such a non-stationary environment, economic agents do not venture in complicated estimations of an intrinsically unpredictable phenomenon. They develop a simple and *persistent* rule of behavior, by which they select a value in the interval  $[m, M]$  depending on their attitude towards uncertainty ( $\alpha$ ). The resulting aggregate R&D investment behavior is then insensitive to unpredictable changes in the profitability conditions of the economy (as they depend on the true  $\lambda_t$ ). In other words, this behavior becomes a *routine*, in that it gives up the goal of estimating what in fact cannot be estimated, and results in a time-invariant, culturally-rooted choice behavior.<sup>16</sup> Whether the routine developed in a certain economy ( $n_\alpha^*$ ) is more or less innovation-prone depends on agents’ tolerance ( $\alpha$ ) towards environmental uncertainty ( $[m, M]$ ).

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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.

<sup>16</sup>With this statement we do not want to deny that this routinized investment behavior may change over time. Recent empirical literature finds that organizational routines are not inert (see for instance Feldman, 2000, 2003). In our framework routinized R&D efforts would in fact respond to changes in the fundamentals of the economy (or even to shocks possibly hitting the economy if they originate from known distributions). We simply say that agents avoid wasting their (limited) cognitive resources in trying to predict the unpredictable, and that they develop routines when facing pervasive uncertainty.

## 6 Welfare Analysis

In this section we compare the laissez-faire equilibrium R&D effort  $n_\alpha^*$  with the one chosen by a social planner seeking to maximize the welfare of the representative agent  $n_\alpha^{sp}$ . 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 ( $\pi_t$ ); 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 holder 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 next innovation unambiguously enhances 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  $\lambda n$  per 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

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

In our framework, however,  $\lambda$  changes over time and is unknown even to the social planner. 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 as

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

The comparison between the laissez-faire equilibrium research effort and the socially optimal one (that is,  $n_{\alpha}^*$  vs.  $n_{\alpha}^{sp}$ ) reveals that, as in Aghion-Howitt (1992), the former value can be higher or lower than the latter, and for exactly 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 Uncertainty Avoidance Index 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:

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

The index ranges from a minimum of  $-150$  to a maximum of  $+230$ . This kind of experiment has been replicated over time - even using different populations, and slightly different questions as a consequence -, and the original country rankings have always been broadly 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 parameter  $\alpha$  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 coefficient  $\alpha$ ), 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. In capturing both uncertainty and uncertainty attitude, the UAI can probably be seen in connection with the perceived variance in the interarrival time of innovations (see Subsection 5.3). This variance is a measure of uncertainty in the innovation process, which is affected by both the ‘subjective’ evaluation of  $\lambda_t$  and by the effect of this evaluation on the amount of R&D efforts ( $n_\alpha^*$ ). It then incorporates both uncertainty and the attitude towards it. In either interpretation the causal mechanism highlighted in the model, according to which a fall in the ambiguity aversion index  $\alpha$  leads to an increase in R&D employment  $n_\alpha^*$ , is well in accord with the negative correlations between UAI and the different measures of R&D activity shown in figures 1-2.

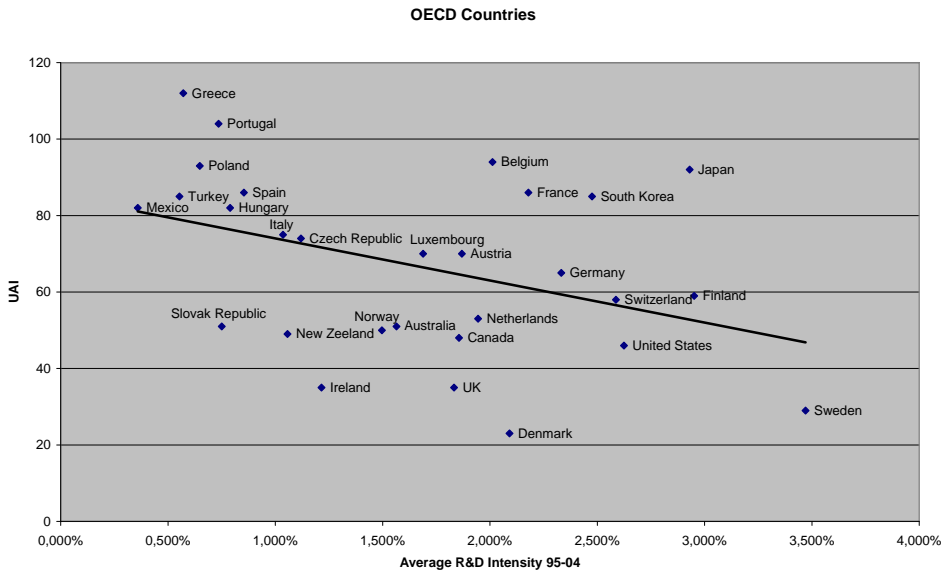


Figure 1: Sources OECD, AMBERD database and national accounts, Hofstede (2001) and own calculations.

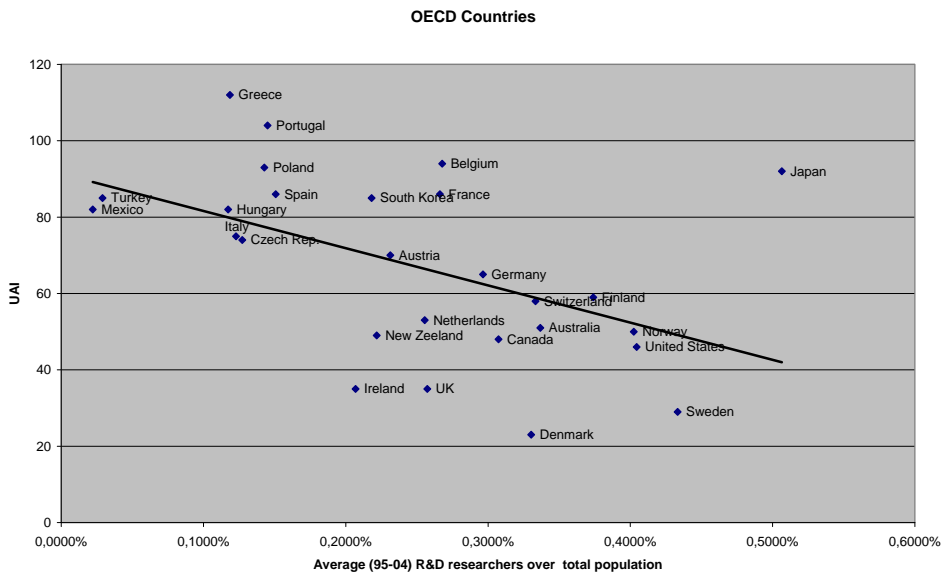


Figure 2: Sources UN demographics statistics, UNESCO UIS data, Hofstede (2001) and own calculations.