

# The dynamics of innovation and risk

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## Abstract

We study the dynamics of an innovative industry when agents learn about the likelihood of negative shocks. Managers can exert risk-prevention effort to mitigate the consequences of shocks. If no shock occurs, confidence improves, attracting managers to the innovative sector. But, when confidence becomes high, inefficient managers exerting low risk-prevention effort also enter. This stimulates growth, while reducing risk-prevention. The longer the boom, the larger the losses if a shock occurs. While these dynamics arise in the first-best, asymmetric information generates excessive entry of inefficient managers, earning informational rents, inflating the innovative sector and increasing its vulnerability.

# 1 Introduction

As vividly illustrated by the boom and bust of the financial sector in the recent decade, innovations can spur rapid growth as well as declining standards, accumulated risk, and finally crises. The goal of this paper is to shed light on the dynamics of innovations and risk. Innovations, by their very nature, are initially untested. Market participants are initially uncertain about the strength, potential and workings of an innovation.<sup>4</sup> They progressively learn about it. Innovative resecuritization techniques offer a good illustration of initial uncertainty and the scope for learning. Collateralized Debt Obligations of Asset Backed Securities offered new ways to reallocate risk, potentially enhancing risk sharing and liquidity. But the reliability and effectiveness of this innovation was not fully clear ex-ante. It depended, in particular, on the degree of correlation between the property markets in different American cities, a parameter about which there was uncertainty. Awareness of uncertainty about the strength of financial innovations was displayed in a “School Brief” published in *The Economist*, in 1999,

“Some of the new financial technologies are, in effect, efforts to bottle up considerable uncertainties. If they work, the world economy will be more stable. If not, an economic disaster might ensue.” Quoted in *The Economist*, September 7th, 2013, page 57

Motivated by these stylized facts, we study uncertainty and learning about the fragility of an innovative industry, i.e., the likelihood that it is hit by negative shock. More precisely, we assume that, with some probability the innovation is strong, while with the complementary probability it is weak. When the innovation is weak, there is a significant risk of negative aggregate shocks, reducing

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<sup>4</sup>We focus on *Bayesian* uncertainty, where agents learn about the parameters of a well defined model. This differs from *Knightian* uncertainty, studied, e.g., by Caballero and Krishnamurthy (2008).

the productivity of all projects in the innovative sector. When the innovation is strong, the likelihood of such negative shocks is lower. As long as there is no aggregate shock, confidence in the strength of the innovation increases. This leads to an increase in the size of the innovative sector. In contrast, when negative shocks occur, this generates pessimism and leads to a decline in the size of the innovative sector.<sup>5</sup>

Our model features managers and investors. The latter can invest in the traditional sector or the innovative one. Because the traditional sector is well known, investors can directly manage their investments in that sector. In contrast, investment in the innovative sector is more challenging. While managers know how to operate in that sector, investors don't. Hence, when opting for the innovative sector, investors must delegate the care of their investments to managers. Thus, investors are principals, while managers are their agents. Correspondingly, we hereafter take the terms “managers” and “agents” as synonymous.

Agents managing investments in the innovative sector can exert costly risk-prevention effort, to reduce downward risk. This is in line with investment situations with bounded upside in which the key is to prevent an unusually low downside. This applies, in general, to the need for due diligence in the purchase of assets, whereby failure to inspect an asset may fail to uncover some hidden flaw. This fits particularly well the purchase of fixed income securities. For example, when investing in a portfolio of Collateralized Debt Obligations, or high yield bonds, the manager can carefully scrutinize the quality of the paper he invests in. Alternatively, if not exerting risk-prevention effort, the manager relies on ready-made evaluations, such as those obtained from credit rating agencies. We consider

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<sup>5</sup>Thus our analysis is in line with Zeira (1987, 1999), Rob (1991), Pastor and Veronesi (2006), and Barbarino and Jovanovic (2007), who show that learning induces fluctuations in industry size.

a continuum of heterogeneous managers. Some have efficient risk-management systems, so that, for them, risk-prevention effort is not very costly. Others have less efficient risk-management systems and incur larger costs when they exert risk-prevention effort.

Our key assumption is that the benefits of risk-prevention effort materialize when the innovation is subsequently hit by a negative shock. When there is no negative shock, innovative projects fare well, even when managers exerted low effort. When a negative shock hits, the projects whose managers exerted high risk-prevention effort are relatively robust, while the other projects are highly likely to fail. This assumption fits the stylized facts from the Tech boom and bust. Market participants who invested without careful scrutiny in dot.com ventures fared relatively well until the bust of March 2000, but then incurred large losses. Another example is momentum-like trading, where, instead of conducting fundamental analysis, fund managers invest in stocks that previously fared well. While such strategy can generate profits in lenient market environments, it runs the risk of large losses when the market is hit by a negative shock.<sup>6</sup> Similarly, institutions which purchased mortgage backed securities based on superficial risk controls and ready-made evaluations such as ratings, made large losses only when the crisis hit, in the summer of 2007. In contrast, those professional investors and investment banks who scrutinized quality lost much less.

For clarity and simplicity, we first analyze the case where effort is observable and contractible. Then we turn to the moral hazard case. With symmetric information, we obtain the following equilibrium dynamics. Initially, when confidence is low (i.e., for a low probability that the innovative sector is strong), only managers with efficient risk-management systems enter, and they exert high

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<sup>6</sup>Daniel and Moskowitz (2012) find that momentum strategies earn negative returns when markets are particularly volatile and declining. Similarly, Daniel, Jagannathan and Kim (2012) find that momentum strategies experience infrequent but severe losses, when the market is turbulent.

risk–prevention effort. At some point, confidence becomes so high that entry becomes profitable for managers with less efficient risk–prevention systems, exerting low effort. This accelerates the growth of the innovative sector, while inducing a decline in risk prevention standards. Thus, our theoretical analysis yields the following implications:

- After strong cumulated performance there is an endogenous decline in risk–prevention standards, with the strongest decline occurring precisely at the time of the sharpest increase in the size of the innovative sector.
- As confidence increases, there is both a decline in the probability of a negative shock and an increase in the size of the aggregate loss in case of shock. This is consistent with the empirical findings of Dell’Ariccia et al (2012) that busts following long booms are worse than those coming after short booms.
- When risk–prevention standards start declining, there is an increase in the cross–sectional variance of the probability of default across managers. If the growth of the innovative sector continues long enough, however, the variance of default probabilities across managers eventually declines.
- When the return on standard investments is low and investors search for yield, the growth of the innovative sector is stronger, but the size of total losses in case of shock is larger.
- As managers are heterogeneous with respect to the cost of effort, while the marginal manager is indifferent between the two sectors, infra–marginal managers in the innovative sector earn quasi–rents, consistent with the findings of Philippon and Resheff (2009). Furthermore, our theory implies that the wage differential between the two sectors should increase with the cumulated performance of the innovative sector.

While the above dynamics arise under symmetric information, in practice innovative industries are likely to be plagued with incentive problems and information asymmetries. The techniques used by managers in the innovative sector are new and difficult to understand for outside investors. The corresponding opacity makes it difficult for the investors to observe, monitor and control the actions of the managers. Therefore, to increase the relevance of our analysis, we extend it to the case where information is asymmetric, as managers' efforts are unobservable by investors.<sup>7</sup> In this richer setting, which we refer to as *moral hazard*, we obtain the following additional implications:

- Moral hazard reduces the ability to ensure that managers exert high risk–prevention effort.

At the same time, when confidence is low, it is not profitable to invest in the innovation if the manager is to exert low risk–prevention effort. Thus, when initial confidence is low and incentive problems are severe, there is no investment in the innovative sector. In a sense the innovation is trapped.<sup>8</sup>

- On the other hand, if confidence is somewhat larger, the innovation grows faster and the innovative sector is larger with incentive problems than without. In the first–best, initially, only managers with efficient risk–prevention systems enter, and they exert high effort. In contrast, under moral hazard, it is difficult to screen efficient managers exerting high effort from less efficient managers exerting low effort. This facilitates the entry of inefficient managers, exerting

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<sup>7</sup>We also assume that managers' effort costs are unobservable. While this does not affect the results when effort is observable, this plays a key role when effort is not observable.

<sup>8</sup>In our analysis, as in the cascade model of Bikhchandani, Hirshleifer and Welch (1992) or the multiplayer bandit of Bolton and Harris (1999), agents don't internalize the positive externalities their own experimentation creates for others. But what precludes optimal experimentation in the present model is moral hazard, which differs from Bikhchandani, Hirshleifer and Welch (1992) or Bolton and Harris (1999).

low risk–prevention effort. Such entry fuels the growth of the innovative sector, and inflates its size relative to the first best.

- In this context, the expected compensation of managers exerting low effort exceeds their productivity. They earn informational rents, at the expenses of the efficient managers exerting high effort.
- This situation is beneficial for the inefficient managers who would not have been hired in the first best, but it is socially costly, as it increases the vulnerability of the innovative sector and the aggregate loss in case of shock.

While our theoretical model could also be applied to nonfinancial innovations, it is particularly appropriate to describe and analyze the dynamics of innovations in the finance sector. Three of the most important features of financial innovations play a key role in our analysis: First, risk–control and management are key to the success of financial innovations, and it is precisely these activities which the managers of our model are in charge of. Second, the complexity and nonphysical nature of financial innovations make it difficult for outside investors to observe finance sector managers actions, which generates moral hazard, as in our model. Third, when financial innovations prove to be weak, this generates severe losses for a large cross–section of financial institutions, again as in our model.

Our theoretical analysis shows that, with imperfect markets, the equilibrium size of the financial sector can exceed its first best counterpart, as in Bolton et al (2013) and Atkeson et al (2013). Yet, our analysis and theirs involve markedly different economic mechanisms. In our paper it is the entry of managers exerting low–risk prevention effort that inflates the financial sector, while in Bolton et al (2013) it is the fact that dealer’s entry in the opaque OTC market worsens adverse selection in the



transparent market, and in Atkeson et al (2013) entry is excessive because of congestion externalities.

Our model involves learning, as in Diamond (1991), Noe and Rebello (2012), Persons and Warther (1997) and Berk and Green (2004). Again, our analysis involves very different economic mechanisms, and generates qualitatively different results. In particular, Diamond (1991)'s result that agents are less likely to be of the risky type after good performance contrasts with our result that risk-prevention standards decline after good performance. Similarly, while in Noe and Rebello (2012) the incentives of the agent improve as the firm is perceived to be less vulnerable, in our model it is the opposite. Also, while in Persons and Warther (1997) there is *positive* skewness in the distribution of outcomes across innovations, so that most innovations perform worse than expected, in our analysis, there is *negative* skewness: after good performance, managers switch to low risk-prevention, creating the risk of unlikely but large aggregate losses. Finally, in Berk and Green (2004), learning about the skills of an individual manager drives the amount of funds this manager is entrusted with. In contrast, we model learning about the industry, driving the aggregate amount of funds delegated to managers. In this context, unlike in Berk and Green (2004), aggregate industry risk varies reflecting i) the likelihood that the industry is strong and ii) the aggregate level of risk-prevention effort.

The next section presents the model. Section 3 examines the case where effort is observable. Section 4 turns to the moral hazard case. Section 5 concludes.

## 2 The model

### 2.1 Agents and goods

Consider an infinite horizon economy, operating in discrete time at periods  $t = 1, 2, \dots$ . At each period, there is a mass-one continuum of competitive managers, indexed by  $i \in [0, 1]$ , and a mass-one continuum of investors. All are risk neutral and have limited liability. In the basic version of our model, with symmetric information, equilibrium is the same irrespective of whether agents live one period or many. When we turn to the moral hazard case (in Section 4), to simplify the contracting problem, we assume market participants live only one period and, at the beginning of each period, a new generation is born.<sup>9</sup>

At the beginning of each period, each investor is endowed with one unit of investment good, while managers have no initial endowment. Investors can invest their initial endowment themselves, an option we hereafter refer to as “self-investment.” The rate of return on self-investment is denoted by  $r$ , i.e., 1 unit of investment good yields  $1 + r$  units of consumption good. Alternatively, each investor can decide to delegate the management of her investment good to a manager operating in the innovative sector. Each manager can handle only one unit of investment – this is the simplest way to model decreasing returns to scale, in the same spirit as Berk and Green (2004). Managers that are not in charge of investments remain in their initial occupation, with opportunity wage normalized to 0. At the end of each period, all market participants consume their share of the consumption good.

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<sup>9</sup>Dynamic contracting under moral hazard and learning can generate rich but complex phenomena. In particular, unobserved shirking can create a wedge between the beliefs of principals and agents. Bergemann and Hege (1998, 2005) and DeMarzo and Sannikov (2008) offer insightful analyses of this problem.

## 2.2 Uncertainty and learning

When a new technology is discovered, its quality is initially untested. Before agents have been able to experiment with it, they are uncertain how it will fare in various circumstances. Correspondingly, agents must learn about the strengths and weaknesses of the innovation. We consider the case where the innovation can be weak or strong and model learning as follows.

Each period, the innovative sector can fare well, which is denoted by  $\xi = 0$ . Alternatively it can be hit by a negative aggregate shock (denoted by  $\xi = 1$ ), reducing the expected productivity of all innovative projects.<sup>10</sup> Initially the likelihood of shocks is uncertain, but all market participants know that the innovation can be strong or weak and that strong innovations are less prone to negative shocks than fragile ones. More precisely, when the innovation is strong, the probability of a negative shock is  $1 - \bar{p}$ . When it is fragile this probability is  $1 - \underline{p} > 1 - \bar{p}$ .

Throughout the paper we assume the occurrence of shocks is observable and contractible. Hence, market participants use past realizations to conduct Bayesian learning about the strength of the innovation. At the beginning of the first period ( $t = 1$ ), they start with the prior probability  $\pi_1$  that the innovation is strong. For  $t > 1$ , denote by  $\pi_t$  the updated probability that the innovation is strong, given the returns realized in the innovative sector at times  $\{1, \dots, t - 1\}$ . When there is no shock, the probability that the innovation is strong is revised upward to:

$$\frac{\bar{p}\pi_t}{\bar{p}\pi_t + \underline{p}(1 - \pi_t)} > \pi_t. \tag{1}$$

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<sup>10</sup>Hereafter, for brevity, we sometimes omit the qualifier “negative”, but when we simply write “shock” we always refer to a negative shock.

If there is a negative shock, the probability that the innovation is strong is revised downward to

$$\frac{(1 - \bar{p})\pi_t}{(1 - \bar{p})\pi_t + (1 - \underline{p})(1 - \pi_t)} < \pi_t.$$

Thus,  $\bar{p} > \underline{p}$  is a key assumption in our model. It implies that weak innovations are more exposed to negative shocks than strong ones, and consequently that when shocks are rare the innovation is likely to be strong. At each point in time  $t$ , the problem faced by all market participants is the same as at  $t - 1$ , except for the difference in the probability that the innovation is strong. The dynamics of the probability ( $\pi_t$ ) that the innovation is strong is one to one with that of the updated probability of a negative shock

$$\theta_t = 1 - (\pi_t \bar{p} + (1 - \pi_t) \underline{p}). \quad (2)$$

We hereafter use  $\theta_t$  as the state variable. When the innovation is known for sure to be weak, i.e.,  $\pi_t = 0$ , then  $\theta_t = 1 - \underline{p}$ . When the innovation is known for sure to be strong, i.e.,  $\pi_t = 1$ , then  $\theta_t = 1 - \bar{p}$ .

### 2.3 Effort, output and costs

Each agent  $i$  can exert high effort ( $e_i = \bar{e}$ ) or low effort ( $e_i = \underline{e}$ ). For simplicity, we normalize  $\bar{e}$  to 1. If there is no shock, for all projects the realization of the output variable  $\tilde{Y}$  is  $Y > 1 + r$  with probability 1, irrespective of effort. If there is a negative shock, with probability  $\mu + (1 - e_i) \frac{\Delta}{1 - \underline{e}}$  a project fails and the realization of  $\tilde{Y}$  is 0. With the complementary probability the project is successful and the realization of  $\tilde{Y}$  is  $Y$ . High managerial effort leads to an improvement in the distribution of output in the sense of first order stochastic dominance. We interpret this in terms of risk-prevention. For example, in a financial context, fund managers and bankers can spend effort and resources on risk-analysis. Such high effort enables them to screen investment opportunities and avoid those with

a large failure risk. In contrast,  $e_i = \underline{e}$  corresponds to weak risk-management practices such as, e.g, exclusive reliance on external credit rating agencies, backward-looking measures of risk or failure to conduct adequate stress-tests as discussed in Ellul and Yerramilli (2010). Such lack of fundamental valuation and risk analysis exposes investments to larger downside risk in case of negative shocks.

While managers all have access to the same type of investment project, they are heterogeneous with respect to the efficiency of their risk management systems. When exerting effort  $e_i$ , manager  $i$  incurs non-monetary cost  $e_i C_i$ .  $C_i$  is distributed over  $[0, C_{\max}]$  with cdf  $F$ . Managers with high  $C$ s have inefficient risk-control systems, making it difficult and costly for them to screen out bad investment projects.

It is very difficult for outside investors to observe and monitor the efficiency of financial firms' risk-management systems. In fact, it is even difficult for supervisors, that are explicitly in charge of such monitoring, and assign teams of highly competent examiners to conduct this task.<sup>11</sup> To reflect this difficulty, we assume, throughout the paper, that costs ( $C_i$ ) are unobservable by investors. When effort is observable, private information on  $C_i$  does not affect equilibrium outcomes, because returns, for a given level of effort, are unaffected by  $C$ . In contrast, when effort is not observable, asymmetric information on  $C_i$  affects equilibrium outcomes, as analysed below, in Section 4.

The unfolding of uncertainty in each period  $t$  is illustrated in Figure 1. As can be seen in the figure, when the manager exerts high effort, the project can fail only with probability  $\mu\theta_t$ . Thus, expected

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<sup>11</sup>For example, one can read in the OCC's Handbook on Large Bank Supervision (2010, pages 2 and 3): "...the OCC assigns examiners to work full-time at the largest institutions... The OCC's large bank supervision objectives are designed to... [e]valuate the overall integrity and effectiveness of risk management systems, using periodic validation through transaction testing... examiners ... attempt to ... determine whether ... bank systems and processes permit management to adequately identify, measure, monitor, and control existing and prospective levels of risk."

surplus (gross of the managerial cost of effort and the outside opportunity wage) is

$$\alpha_t = (1 - \mu\theta_t)Y - (1 + r). \quad (3)$$

The larger the probability  $\theta_t$  that there is a negative shock, the lower the expected surplus  $\alpha_t$ . We assume however (to limit the number of cases), that, even when the innovation is known for sure to be fragile,  $\alpha_t \geq 0$ , that is

$$1 - \underline{p} \leq \frac{1}{\mu} \frac{Y - (1 + r)}{Y}. \quad (4)$$

When the manager exerts low effort, on the other hand, the gross expected surplus is

$$\alpha_t - \theta_t \Delta Y. \quad (5)$$

The larger the probability of a shock, the higher the value of risk-prevention,  $\theta_t \Delta Y$ . Thus, since  $\alpha_t$  is decreasing in  $\theta_t$ ,  $\alpha_t - \theta_t \Delta Y$ , the expected surplus under low effort, is also decreasing in  $\theta_t$ . Finally, we assume that

$$C_{\max} > \max\left[(1 - \mu(1 - \bar{p}))Y - (1 + r), \frac{(1 - \mu(1 - \bar{p}))Y - (1 - \bar{p})\Delta Y - (1 + r)}{1 - \underline{e}}\right] \quad (6)$$

so that, even when the innovation is known for sure to be strong, it is suboptimal to hire the least efficient manager. This implies that the mass of managers who could operate efficiently in the innovative sector is lower than the mass of investors, which can be interpreted in terms of scarcity of managers. Assumption (6) is made for simplicity. Our qualitative results would still obtain under weaker assumptions.

Throughout the paper we assume output realizations are observable and contractible. Within each period  $t$ , the sequence of actions is the following:

- Investors and managers start with the same belief  $\pi_t$  that the innovation is strong.

- Investors and managers meet in the labour market.
- Managers who have been hired exert high or low effort.
- There is a negative shock or not, and this is observable by all market participants.
- For each project, the investment is successful and yields  $Y$  or fails and yields 0.

### 3 The dynamics of innovative activities when effort is observable

In this section we consider the case where efforts ( $e_i$ ) are observable and contractible, so that there are no incentive problems.

#### 3.1 Equilibrium

Investors and managers meet in the labour market. There are two submarkets, one for managers exerting high effort, the other for managers exerting low effort. A compensation contract is a mapping of all the observable variables into the compensation of a manager. In the present section, the observable variables in period  $t$  are the state variable  $\theta_t$ , the output of the project  $\tilde{Y}$ , whether a shock occurred or not  $\xi_t$ , and the effort of the manager. In the observable effort case, the only thing that matters, both for the investor and the manager, is the expected compensation of the manager for a given  $\theta_t$  and effort.<sup>12</sup>

We denote by  $\bar{m}$  the compensation contract for managers hired to exert high effort, and by  $\underline{m}$  the contract for low effort. For simplicity we assume market participants are competitive. Thus, they

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<sup>12</sup>In the next section, we consider the unobservable effort case, where the precise mapping between observable variables and compensation matters, because it affects incentives.

take the equilibrium contracts as given. The equilibrium condition is that labour supply equals labour demand. Labour supply in a given submarket is the mass of managers who (weakly) prefer to be hired in that submarket rather than not being hired or operating in the other submarket. Labour demand is the mass of investors who (weakly) prefer to invest in this market rather than self-investing or operating in the other market.

Market clearing implies

$$E[\bar{m}|\bar{e}, \theta_t] = \alpha_t, E[\underline{m}|\underline{e}, \theta_t] = \max[\alpha_t - \theta_t \Delta Y, 0]. \quad (7)$$

When  $\alpha_t - \theta_t \Delta Y \geq 0$ , (7) means that investors are indifferent between self-investment, investment with high effort and investment with low effort. When  $\alpha_t - \theta_t \Delta Y < 0$ , it means investors are indifferent between self-investment and investment with high effort. To see why (7) is necessary for market clearing, consider the case where  $\alpha_t - \theta_t \Delta Y < 0$ . In that case suppose we had  $E[\bar{m}|\bar{e}, \theta_t] < \alpha_t$ . Then all investors would prefer to hire managers to exert high effort, i.e., labour demand in the market for managers exerting high effort would be equal to one. Yet, labour supply could not exceed  $F(E[\bar{m}|\bar{e}, \theta_t])$ , which is the mass of managers with cost of effort  $C_i < E[\bar{m}|\bar{e}, \theta_t]$ . Since this mass is strictly lower than one (because of (6)), the market would not clear. Thus, when  $\alpha_t - \theta_t \Delta Y < 0$ , market clearing entails  $E[\bar{m}|\bar{e}, \theta_t] = \alpha_t$  as illustrated in Figure 2. Similar arguments apply for the other cases.

(7) implies that, whenever an investor hires a manager, the latter captures all the surplus generated by their interaction. This is in line with Berk and Green (2004), where the economic rents flow through to the managers who create them, not to the investors who invest in them. Our result reflects the assumption that managers are heterogeneous and, while the best of them are very good, the worse ones are quite inefficient, as stated in (6). Thus, highly talented managers are scarce. And this matters



because each manager can handle only one project and managers have different  $C_i$ s.

Manager  $i$  applies for a job requesting high effort if

$$E[\bar{m}|\bar{e}, \theta_t] - C_i \geq \max[0, E[m|e, \theta_t] - \underline{e}C_i], \quad (8)$$

while she applies for a job requesting low effort if

$$E[m|e, \theta_t] - \underline{e}C_i \geq \max[0, E[\bar{m}|\bar{e}, \theta_t] - C_i], \quad (9)$$

and otherwise chooses to remain in her initial occupation. Hence manager  $i$  choosing between high-effort, low-effort and staying out of the innovative sector obtains the following expected gain

$$\max[E[\bar{m}|\bar{e}, \theta_t] - C_i, E[m|e, \theta_t] - \underline{e}C_i, 0]. \quad (10)$$

Substituting (7) into (10), the expected gain obtained by manager  $i$  in the innovative sector is

$$\max[\alpha_t - C_i, \alpha_t - \theta_t \Delta Y - \underline{e}C_i, 0]. \quad (11)$$

Since (11) is also equal to the social value created by the employment of manager  $i$  in the innovative sector, we have that market equilibrium is Pareto optimal. It is natural, since the market is competitive and frictionless, that the first welfare theorem holds.

Denoting,

$$\beta_t = \frac{\theta_t \Delta Y}{1 - \underline{e}}, \quad \gamma_t = \frac{\alpha_t - \theta_t \Delta Y}{\underline{e}},$$

(7), (8) and (9) imply that managers choosing high effort are such that,

$$C_i \leq \min[\alpha_t, \beta_t]. \quad (12)$$

while managers choosing low effort are such that<sup>13</sup>

$$\beta_t \leq C_i \leq \gamma_t. \quad (13)$$

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<sup>13</sup>Note that, as can be seen in Figure 3, when  $\alpha_t < \beta_t$ , the interval  $[\beta_t, \gamma_t]$  does not exist.

If  $C_i = \alpha_t$ , agent  $i$  is indifferent between effort and staying out of the innovative sector. If  $C_i = \beta_t$ , agent  $i$  is indifferent between effort and no effort. If  $C_i = \gamma_t$ , agent  $i$  is indifferent between low effort and staying out of the innovative sector. Thus, when  $C_i = \alpha_t = \beta_t$ , we have  $C_i = \gamma_t$ . Define  $\hat{\theta}$  as the probability of a negative shock such that  $\beta_t = \gamma_t = \alpha_t$ . Simple computations yield

$$\hat{\theta} = \frac{Y - (1+r)}{Y} \frac{1}{\mu + \frac{\Delta}{1-\varepsilon}}. \quad (14)$$

To focus on the interesting case, we assume that  $\hat{\theta}$  is in the support of  $\theta$ , i.e.,  $1 - \bar{p} < \hat{\theta} < 1 - \underline{p}$ .

$\beta_t$  increases linearly in  $\theta_t$ , while  $\gamma_t$  and  $\alpha_t$  decrease linearly. These functions are as illustrated in Figure 3. Inspecting the figure and using conditions (12) and (13), one sees that, for  $\theta_t > \hat{\theta}$ , managers with  $C_i \leq \alpha_t$  choose to be employed to exert high effort, while managers with  $C_i > \alpha_t$  prefer to stay out of the innovative sector. For  $\theta_t \leq \hat{\theta}$ , managers with  $C_i \leq \beta_t$  choose to be employed to exert high effort, managers with  $\beta_t \leq C_i \leq \gamma_t$  choose to be employed to exert low effort, and managers with  $C_i > \gamma_t$  prefer to stay out of the innovative sector. Thus, noting that  $\theta_t$  declines as long as the industry is not hit by a negative shock, we can state our first proposition.

**Proposition 1** *When  $\theta_t \geq \hat{\theta}$ , all agents hired to manage investment exert high effort, and their expected compensation,  $E[\bar{m}|\bar{e}, \theta_t] = \alpha_t$  as well as their mass,  $F(\alpha_t)$ , grow as long as the industry is not hit by a shock.*

*When  $\theta_t < \hat{\theta}$ , while a mass  $F(\beta_t)$  of agents exert high effort, a mass  $F(\gamma_t) - F(\beta_t)$  exert low effort. The former earn expected compensation,  $E[\bar{m}|\bar{e}, \theta_t] = \alpha_t$ , the latter earn  $E[\underline{m}|\underline{e}, \theta_t] = \alpha_t - \theta_t \Delta Y$ . Both expected compensations, and also the mass of managers in the innovative industry, grow as long as the industry is not hit by a shock.*

*When there is a negative shock, compensation and the number of managers working in the innovative industry suddenly drop.*

Managers who are more efficient at controlling risks (with low  $C_i$ ) are more likely to be employed in jobs requesting high effort. They correspondingly earn larger compensation. Once confidence has improved so much that  $\theta_t$  becomes lower than  $\hat{\theta}$ , the increase in the fraction of managers exerting low effort tends to push average compensation down. But, controlling for the type of tasks (i.e., high or low effort), compensation continues to grow as long as the innovation is successful.

### **3.2 Infra–marginal rents**

Infra–marginal managers’ rents are equal to the difference between their expected compensation and their cost of effort. Thus manager  $i$  obtains rent equal to

$$\mathcal{R}(C_i, \theta_t) = \max[\alpha_t - C_i, \alpha_t - \theta_t \Delta Y - \underline{e}C_i, 0]. \quad (15)$$

By construction, except for the marginal agent, managers employed in the innovative sector earn strictly positive rents, reflecting the above mentioned scarcity of highly talented managers. Thus we can state the following corollary.

**Corollary 1:** *The expected compensation of managers employed in the innovative sector exceeds the sum of their cost of effort and their outside opportunity wage. The corresponding infra–marginal rents ( $\mathcal{R}(C_i, \theta_t)$ ) increase, for all managers, as confidence in the strength of the innovative sector increases.*

The quasi–rents in Corollary 1 reflect managers’ heterogeneity, similarly to Berk and Green (2004).

### 3.3 Implications of the model with observable effort

#### 3.3.1 Growth and compensation in the innovative sector

As long as there is no negative shock, confidence in the innovation increases, i.e.,  $\theta_t$  decreases. Proposition 1 implies that this leads to an increase in the mass of agents hired to manage investments. When  $\theta_t$  gets lower than  $\hat{\theta}$ , the innovation is perceived to be so strong that, even with low effort, it can outperform self-investment. This spurs the entry of relatively inefficient managers, planning to exert low effort. This, in turn, can induce an increase in the growth of the innovative sector. As long as  $\theta_t > \hat{\theta}$ , the size of the innovative sector is  $F(\alpha_t)$ . Thus, the growth of the innovative sector is given by

$$\frac{dF(\alpha_t)}{dt} = \frac{dF(\alpha_t)}{d\theta_t} \frac{d\theta_t}{dt} = f(\alpha_t) \frac{d\alpha_t}{d\theta_t} \frac{d\theta_t}{dt} = -f(\alpha_t) \mu Y \frac{d\theta_t}{dt} = f(\alpha_t) \mu Y \left| \frac{d\theta_t}{dt} \right|.$$

As soon as  $\theta_t < \hat{\theta}$ , the size of the innovative sector is  $F(\gamma_t)$ . Thus, the growth of the innovative sector is given by

$$\frac{dF(\gamma_t)}{dt} = \frac{dF(\gamma_t)}{d\theta_t} \frac{d\theta_t}{dt} = f(\gamma_t) \frac{d\gamma_t}{d\theta_t} \frac{d\theta_t}{dt} = -f(\gamma_t) \frac{(\mu + \Delta)Y}{\underline{e}} \frac{d\theta_t}{dt} = f(\gamma_t) \frac{(\mu + \Delta)Y}{\underline{e}} \left| \frac{d\theta_t}{dt} \right|.$$

Noting that  $\underline{e} < \bar{e} = 1$  and that, at  $\theta_t = \hat{\theta}$ ,  $f(\alpha_t) = f(\gamma_t)$ , we have that the growth of the finance sector just before  $\hat{\theta}$ :  $\frac{dF(\alpha_t)}{dt}$ , is lower than its counterpart just after  $\hat{\theta}$ :  $\frac{dF(\gamma_t)}{dt}$ . Otherwise stated, the growth of the innovative sector induced by the absence of shock increases when  $\theta_t$  hits  $\hat{\theta}$ . Graphically, this corresponds to the fact that, in Figure 3, the absolute value of the slope of  $\gamma_t$  is larger than that of the slope of  $\alpha_t$ .

Thus, noting that confidence increases with the time without negative shocks and also with the cumulated performance of the innovative sector, which can be empirically measured by cumulated operating profits, we can state our first implication.

**Implication 1:** *The size of the innovative sector is increasing in the length of the period without negative shock and the cumulative performance of the innovation. After sustained performance, there is an increase in the growth of the innovative sector.*

Since Corollary 1 implies that expected compensation increases with the confidence in the innovation, we can state the following implication.

**Implication 2:** *The longer the period without negative shock and the larger the cumulative performance of the innovation, the higher the wage in the innovative sector.*

Our theoretical result that compensation in the innovative sector trends upwards is in line with the empirical findings of Philippon and Resheff (2009).

### 3.3.2 Deteriorating standards in the innovative sector

While, when  $\theta_t > \hat{\theta}$ , all managers exert high effort, after sustained success  $\theta_t$  gets lower than  $\hat{\theta}$ , and an increasing fraction of managers are hired without being requested to exert high effort. Correspondingly, when  $\theta_t$  gets below  $\hat{\theta}$ , there is a decline in the proportion of managers exerting high risk-prevention effort. More precisely, when  $\theta_t < \hat{\theta}$  the average effort level is

$$F(\beta_t) + \frac{F(\gamma_t) - F(\beta_t)}{F(\gamma_t)} \underline{e} = \underline{e} + (1 - \underline{e}) \frac{F(\beta_t)}{F(\gamma_t)},$$

which is increasing in  $\theta_t$ , since  $F(\beta_t)$  is increasing in  $\theta_t$  while  $F(\gamma_t)$  is decreasing. Thus, as confidence increases (and  $\theta_t$  goes down), there is a decline in the average level of effort requested, coinciding with a decline in the average efficiency of risk-management systems. Interpreting this as a decline in risk-prevention standards, we obtain the following implication.

**Implication 3:** *After sustained success, there is a decline in risk-prevention standards, starting at the time at which the growth of the innovative sector accelerates.*

Implication 3 is consistent with the empirical findings of Dell’Ariccia et al (2008) who, e.g., write in their abstract: “This paper links the current sub-prime mortgage crisis to a decline in lending standards associated with the rapid expansion of this market.” Dell’Ariccia et al. (2008) relate their empirical findings to asymmetric information based theories of financial accelerators (see Bernanke and Gertler, 1998, and Kiyotaki and Moore, 1997). Yet, our analysis shows that agency problems are not needed to rationalize these findings.<sup>14</sup> The decline in standards in Implication 3 corresponds to the entry of financial intermediaries with weaker and weaker risk-control systems. To test this implication, empirical proxies for the strength of risk-control systems are needed. One could rely on the Risk Management Index developed by Ellul and Yerramilli (2010).<sup>15</sup>

### 3.3.3 Unlikely but large aggregate losses

The probability of a negative shock ( $\theta_t$ ) goes down with the number of periods without a shock. For  $\theta_t \geq \hat{\theta}$ , the mass of failing projects in case of a negative shock is

$$F(\alpha_t)\mu.$$

This decreases with  $\theta_t$ , i.e., increases with the confidence in the innovation, simply because, as confidence grows, more projects are operated in the innovative sector. When  $\theta_t < \hat{\theta}$  the mass of failures in

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<sup>14</sup>In the next section, however, we show that these problems are exacerbated by information asymmetry.

<sup>15</sup>Consistent with our theoretical analysis, Ellul and Yerramilli (2010) find that financial institutions with stronger risk-control systems in 2006 had lower exposure to private-label mortgage-backed securities, had a smaller fraction of non-performing loans and had lower downside risk during the crisis years.

case of negative shock becomes

$$F(\alpha_t)\mu + [F(\gamma_t) - F(\alpha_t)]\mu + [F(\gamma_t) - F(\beta_t)]\Delta,$$

which is also decreasing in  $\theta_t$ . This reflects two evolutions: First, as above, as confidence increases, the number of projects operated in the innovative sector increases. Second, as confidence increases, an increasing fraction of the projects is operated with low risk–prevention effort. Thus we can state the next implication.

**Implication 4:** *As the probability of a shock ( $\theta_t$ ) declines, the size of the loss in case of shocks increases. After a sustained period of success, when  $\theta_t$  gets lower than  $\hat{\theta}$ , there is an increase in the growth of the innovative sector and the mass of failures in case of shock.*

Our theoretical analysis thus implies that long awaited shocks, that come after a period of sustained performance and growing confidence, are more severe than shocks happening during the early developments of the innovation.<sup>16</sup> This is in line with the empirical finding by Dell’Ariccia et al (2012) that busts following long booms are worse than busts coming after short booms. The pattern generated by our model could look like a bubble followed by a crash. Yet it simply reflects how the optimal level of investment and effort adjusts as agents learn about the strength of the innovation.

### 3.3.4 The cross–section of failure probabilities

For  $\theta_t \geq \hat{\theta}$ , the failure probability for each project operated in the innovative sector is  $\theta_t\mu$ . For  $\theta_t < \hat{\theta}$  the failure probability in the innovative sector remains equal to  $\theta_t\mu$  for projects with  $C_i \leq \beta_t$ , but it

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<sup>16</sup>Our analysis of the implications of Proposition 1 for the dynamics of risk is complemented, in Appendix 2, by an analysis of the implications of our model for the dynamics of two popular measures: Value at Risk and Expected Shortfall.

is  $\theta_t(\mu + \Delta)$  for projects with  $C_i > \beta_t$ . Thus, for  $\theta_t < \hat{\theta}$ , the cross-sectional average default rate in the innovative sector is

$$\theta_t \left\{ \frac{F(\beta_t)}{F(\gamma_t)} \mu + \frac{F(\gamma_t) - F(\beta_t)}{F(\gamma_t)} (\mu + \Delta) \right\} = \theta_t \left\{ \mu + \left(1 - \frac{F(\beta_t)}{F(\gamma_t)}\right) \Delta \right\}.$$

This is the product of the probability of shock ( $\theta_t$ ) by the cross-sectional average probability of default in case of shock. The latter increases with the confidence in the innovative sector.

While for  $\theta_t \geq \hat{\theta}$ , all managers operating in the innovative sector have the same probability of default:  $\theta_t \Delta$ , for  $\theta_t < \hat{\theta}$ , a fraction  $F(\beta_t)/F(\gamma_t)$  of the managers have default rate in case of shock equal to  $\mu$ , while for the others it is  $\mu + \Delta$ . Hence, for  $\theta_t \geq \hat{\theta}$ , the cross-sectional variance of default probabilities in case of shock is 0, while, for lower values of  $\theta_t$ , it is

$$2 \frac{F(\beta_t)}{F(\gamma_t)} \left(1 - \frac{F(\beta_t)}{F(\gamma_t)}\right) \Delta^2.$$

As  $\theta_t$  crosses  $\hat{\theta}$ ,  $\frac{F(\beta_t)}{F(\gamma_t)}$  is initially close to one. Then it decreases with further increases in confidence. Correspondingly, the cross-sectional variance of default probabilities in case of shock is initially very small, but increases as confidence builds up. On the other hand, if  $\theta_t$  decreases enough for  $\frac{F(\beta_t)}{F(\gamma_t)}$  to reach 1/2, then further increases in confidence reduce this cross-sectional variance. The intuition is the following. As long as  $\theta_t > \hat{\theta}$ , all managers exert high effort, so that there is no cross-sectional variation in the probability of default in case of shock. When  $\theta_t$  crosses  $\hat{\theta}$  from above, an initially small but gradually increasing fraction of managers exerts low effort. Correspondingly, for values of  $\theta_t$  below  $\hat{\theta}$ , but not too far from it, heterogeneity in effort exertion across managers increases with confidence. But, for very low values of  $\theta_t$ , the majority of managers exert low effort, and further decreases in  $\theta_t$  increase this majority, thereby reducing the heterogeneity in default probabilities. Correspondingly,



the cross-sectional variance of default probabilities across managers is inverse-U shaped in  $\theta_t$ . Our next implication summarizes this discussion:

**Implication 5:** *As confidence in the innovation improves, the average default rate in case of shock increases, while the cross-sectional variance of default rates first increases and then decreases.*

To test Implication 5, one needs empirical proxies for failure probabilities. One could rely on put options with different strikes, on credit risk implied by interest rates, or on Credit Default Swap prices, for the market as well as for individual names.

### 3.3.5 Search for yield and the dynamics of the innovative sector

When  $r$  is low, the return on self-investment is low, which leads investors to search for yield. Other things equal, a decrease in  $r$  raises  $\alpha_t$  and  $\hat{\theta}$ . This accelerates the entry of managers exerting low effort, and the growth of the innovative industry, but also increases the size of total losses in case of negative shock. This is stated in our next implication.

**Implication 6:** *The lower  $r$ , the more investors search for yield, the larger the size of the innovative sector, and the larger the size of total losses in case of shock.*

## 4 The dynamics of innovative activities under moral hazard

The equilibrium analyzed above corresponds to the perfect market case. In practice, however, innovative industries are likely to be plagued with information asymmetries. To shed light on the conse-

quences of these problems, we now turn to the case where efforts ( $e_i$ ) are unobservable by investors.<sup>17</sup>

We hereafter refer to this situation as *moral hazard*.

While in the first-best it was sufficient to consider the expected compensation of managers, under moral hazard, the precise mapping from observable outcomes to transfers must now be specified. Because of limited liability of investors, when the realization of  $\tilde{Y}$  is 0 the compensation of the manager is also 0. Hence, we need only consider four transfers:  $\bar{m}(\xi = 0)$  when the agent who is requested to exert high effort is successful and there is no shock,  $\bar{m}(\xi = 1)$  when the agent who is requested to exert high effort is successful in spite of a shock, and  $\underline{m}(\xi = 0)$  and  $\underline{m}(\xi = 1)$  for the corresponding outcomes when the agent is requested to exert low effort.

#### 4.1 Equilibrium

When confidence in the innovation is strong enough, the expected surplus is so large that the first-best allocation is incentive compatible, in spite of the unobservability of effort. To show this, we exhibit a contract,  $m$  (offered to managers exerting high-effort as well as to those exerting low effort) that implements the first best allocation and is incentive compatible when  $\theta_t$  is large enough. This contract is such that  $m(\xi = 1) = Y$ . Since managers receive all the output in case of shock (which is the only case where effort matters), it is in their own interest to choose the first-best level of effort. Consider for example the incentive compatibility condition for high-effort:

$$E[m|\bar{e}, \theta_t] - C_i \geq E[m|\underline{e}, \theta_t] - \underline{e}C_i, \quad (16)$$

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<sup>17</sup>Our modelling of the unobservability of effort is similar to that in Holmstrom and Tirole (1997). In our model, however, unlike in Holmstrom and Tirole, i) the consequences of the level of effort depend on whether there is an aggregate shock or not, and ii) the cost of effort is not observable by investors.

that is

$$C \leq \frac{\theta \Delta m(\xi = 1)}{1 - e}. \quad (17)$$

With  $m(\xi = 1) = Y$ , (17) simplifies to

$$\frac{\theta_t \Delta Y}{1 - e} \geq C_i,$$

which is the condition under which, in the first best, a manager entering the innovative sector prefers to exert high effort rather than low effort. Furthermore, given that  $m(\xi = 1) = Y$ , investors break even if and only if

$$(1 - \theta_t)[Y - m(\xi = 0)] = 1 + r.$$

This is compatible with the limited-liability constraint that  $m(\xi = 0) \geq 0$  if and only if

$$\theta_t \leq \frac{Y - (1 + r)}{Y}.$$

Finally, since investors just break even and managers exert the efficient level of effort, managers obtain the entire surplus when they enter the innovative sector. Consequently, it is in their own interest to make the entry decisions that are first-best optimal. Thus, we can state the following proposition:

**Proposition 2:** *When  $\theta_t \leq \frac{Y - (1 + r)}{Y}$ , equilibrium is the same with or without moral hazard.*

Hereafter, we restrict attention to the more interesting case where moral hazard matters, i.e, we focus on values of  $\theta_t$  above  $\frac{Y - (1 + r)}{Y}$ . An important feature of equilibrium dynamics in the first-best is the switch from the equilibrium regime where all managers exert effort (arising for  $\theta_t \geq \hat{\theta}$ ), to that in which some exert low effort. Since the choice of effort level is the key decision in our moral hazard model, it is important to consider the values of  $\theta_t$  for which the switch from high to low effort can

occur. Since we focus on  $\theta_t > \frac{Y-(1+r)}{Y}$ , this requires that  $\hat{\theta} > \frac{Y-(1+r)}{Y}$ . This inequality is equivalent to

$$1 - \underline{e} > \frac{\Delta}{1 - \mu}, \quad (18)$$

which we assume hereafter. The interpretation of (18) is the following: The left-hand-side is the additional amount of effort needed to exert high risk-prevention. The right-hand-side is the relative increase in risk avoided by exerting high effort. Condition (18) states that the cost of switching to high effort (proportional to left-hand-side) is relatively large compared to the benefit (proportional to the right-hand-side). In that case, the switch from high to low effort occurs relatively early. That is,  $\hat{\theta}$  is relatively large, larger than  $\frac{Y-(1+r)}{Y}$ .

We now establish, that when  $\theta_t > \frac{Y-(1+r)}{Y}$ , under moral hazard, two distinct contracts cannot be offered in equilibrium. Suppose by contradiction that two distinct contracts are offered, one inducing high effort, the other low effort.<sup>18</sup> As in the first-best (see equation (7)), market clearing and the scarcity of managers imply that investors must exactly break even on each contract. Hence, the expected pay-offs, and the decisions of managers (high effort, low effort, no participation) must be exactly the same as in Proposition 1. Now, Proposition 1 implies that there are two active contracts only when  $\theta_t < \hat{\theta}$ , and that contract  $\bar{m}$  (compensating high effort) is chosen by all managers such that

$$C_i \leq \beta_t = \frac{\theta_t \Delta Y}{1 - \underline{e}}. \quad (19)$$

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<sup>18</sup>We show in appendix that one can also rule out situations where i) one of the two contracts would attract both managers exerting high effort and managers exerting low effort, or ii) the two contracts would attract managers exerting high effort and managers exerting low effort.

Similarly to (17), the incentive compatibility condition is

$$C_i \leq \frac{\theta_t \Delta \bar{m}(\xi = 1)}{1 - \underline{e}} \quad (20)$$

for all the managers  $i$  choosing contract  $\bar{m}$ . For the marginal manager (19) holds as an equality and (20) can hold only if  $\bar{m}(\xi = 1) = Y$ . As shown above, in the proof of Proposition 2,  $\bar{m}(\xi = 1) = Y$  is compatible with limited liability only when  $\theta_t \leq \frac{Y - (1+r)}{Y}$ , which is ruled out by construction. This shows, by contradiction, that there is always at most one active contract at equilibrium. Hence, we can state the following proposition:

**Proposition 3:** *Under moral hazard, when (18) holds and  $\theta_t > \frac{Y - (1+r)}{Y}$ , at most one contract is offered at equilibrium.*

Our third, striking, result is that, contrarily to the case where effort is observable, moral hazard implies that there is always a positive fraction of active managers that exert low effort at equilibrium. Again, the proof proceeds by contradiction. Suppose all active managers would exert high effort. Then equilibrium would involve a unique contract,  $m$ .  $m$  should be such that investors would at least break even, i.e.,

$$(1 - \theta_t)m(\xi = 0) + \theta_t(1 - \mu)m(\xi = 1) \leq (1 - \theta_t\mu)Y - (1 + r) \equiv \alpha_t. \quad (21)$$

Since manager's limited liability implies  $m(\xi = 0) \geq 0$ , (21) implies

$$m(\xi = 1) \leq \frac{\alpha_t}{\theta_t(1 - \mu)}.$$

Consequently

$$\theta_t \Delta m(\xi = 1) \leq \frac{\alpha_t \Delta}{(1 - \mu)} < \alpha_t(1 - \underline{e}),$$

where the second inequality stems from (18). Thus, the marginal manager, with cost of effort  $C_i = \alpha_t$ , would strictly prefer to exert low effort, which establishes the contradiction. We can thus state the following proposition:

**Proposition 4:** *Under moral hazard, when (18) holds and  $\theta_t > \frac{Y-(1+r)}{Y}$ , there is always a positive fraction of active managers that exert low effort at equilibrium.*

We now characterize the equilibrium arising in that case. We know that it must be a pooling equilibrium, in which only one contract,  $m$ , is offered and some of the managers accepting it exert high effort while others exert low effort. Denoting

$$\underline{C} = \frac{\theta_t \Delta m(\xi = 1)}{1 - \underline{e}}, \quad (22)$$

and

$$\bar{C} = \frac{(1 - \theta_t)m(\xi = 0) + \theta_t(1 - \mu - \Delta)m(\xi = 1)}{\underline{e}}, \quad (23)$$

the managers who prefer high effort than low effort are those with  $C_i \leq \underline{C}$ , while those who prefer to be hired and exert low effort are such that  $\underline{C} \leq C_i \leq \bar{C}$ .

The market clearing condition, requiring that investors earn zero-profit, is

$$(1 - \theta_t)m(\xi = 0) + \theta_t(1 - \mu - \Delta x)m(\xi = 1) = (1 - \theta_t(\mu + \Delta x))Y - (1 + r), \quad (24)$$

where  $x$  is the fraction of the managers hired in the innovative sector who exert low effort, i.e.,

$$x = 1 - \frac{F(\underline{C})}{F(\bar{C})} = 1 - \frac{F\left(\frac{\theta_t \Delta m(\xi=1)}{1-\underline{e}}\right)}{F\left(\frac{(1-\theta_t)m(\xi=0)+\theta_t(1-\mu-\Delta)m(\xi=1)}{\underline{e}}\right)}.$$

A contract such that  $m(\xi = 0) > 0$  cannot be an equilibrium. Indeed an investor could undercut this contract by offering another one with a lower  $m(\xi = 0)$  and a larger  $m(\xi = 1)$ , in such a way

that the expected gain for a manager exerting low effort would be the same (leaving  $\underline{C}$  unchanged) while increasing the gain from high effort (thus raising  $\bar{C}$ ).<sup>19</sup> This would attract exactly the same managers, but a higher fraction of them would make an effort, thus generating positive expected gains for the investors. Hence, in equilibrium, we must have

$$m(\xi = 0) = 0. \quad (25)$$

Thus,  $x$  rewrites as

$$x = 1 - \frac{F\left(\frac{\theta_t \Delta m(\xi=1)}{1-\underline{e}}\right)}{F\left(\frac{\theta_t(1-\mu-\Delta)m(\xi=1)}{\underline{e}}\right)}.$$

For simplicity, we hereafter assume costs are uniformly distributed over  $[0, C_{\max}]$ .<sup>20</sup> Then the fraction of managers exerting low effort simplifies to

$$x = 1 - \frac{\underline{e}}{1-\underline{e}} \frac{\Delta}{1-\mu-\Delta}. \quad (26)$$

The condition under which  $m(\xi = 1)$  is non-negative is

$$[1 - \theta_t(\mu + x\Delta)]Y - (1 + r) \geq 0, \quad (27)$$

which simplifies to

$$\theta_t \leq \frac{1}{\mu + x\Delta} \frac{Y - (1 + r)}{Y}, \quad (28)$$

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<sup>19</sup>It is indeed possible to increase  $m(\xi = 1)$  since it is less than  $Y$ . To see this, consider the market clearing condition, which implies, when  $m(\xi = 0) > 0$ , that  $m(\xi = 1) < [(1 - \theta_t(\mu + \Delta x))Y - (1 + r)](\theta_t(1 - \mu - \Delta x))^{-1}$ , which is decreasing in  $\theta_t$ . Now, Proposition 4 assumes  $\theta_t > (Y - (1 + r))/Y$ , thus  $m(\xi = 1)$  is lower than  $[Y - (\mu + \Delta x)(Y - (1 + r)) - (1 + r)]((1 - \mu - \Delta x)\frac{Y - (1 + r)}{Y})^{-1}$  which simplifies to  $Y$ .

<sup>20</sup>The result that  $x$  is a constant obtains whenever  $f(m)$ , which can be interpreted as labor supply, has constant elasticity. More generally, if elasticity is nondecreasing, the equilibrium is unique and exhibits the additional property that  $x$  increases with the confidence in the innovation.

If (28) does not hold, there is a market breakdown and no manager is hired in the innovative sector. Otherwise,  $m(\xi = 1)$  is non-negative and is obtained by substituting  $m(\xi = 0) = 0$  and (26) into (24)

$$m(\xi = 1) = \frac{(1 - \theta_t(\mu + \Delta x))Y - (1 + r)}{\theta_t(1 - \mu - \Delta x)}, \quad (29)$$

Substituting (26), (25) and (29) into (23), we have

$$\bar{C} = \frac{1 - \mu - \Delta}{1 - \mu - \Delta \left[ 1 - \frac{\underline{\epsilon}}{1 - \underline{\epsilon}} \frac{\Delta}{1 - \mu - \Delta} \right]} \frac{(1 - \theta_t(\mu + \Delta x))Y - (1 + r)}{\underline{\epsilon}}, \quad (30)$$

which is linear and decreasing in  $\theta_t$ . The above analysis leads to our next proposition, illustrated in Figure 4.

**Proposition 5:** *Under moral hazard, when (18) hold and costs are uniformly distributed over  $[0, C_{\max}]$ , equilibrium is as follows.*

i) *When*

$$\theta_t > \frac{1}{\mu + x\Delta} \frac{Y - (1 + r)}{Y}, \quad (31)$$

*no manager is hired in the innovative sector.*

ii) *When*

$$\frac{1}{\mu + x\Delta} \frac{Y - (1 + r)}{Y} \geq \theta_t > \frac{Y - (1 + r)}{Y},$$

*there exists a pooling equilibrium, in which only one contract  $m$  is offered, a fraction  $x$  of the managers working in the innovative sector exerts low effort, and the complementary fraction exerts high effort. The average expected compensation of managers is given by the left-hand-side of (27), which increases as confidence in the innovative sector improves.*

The intuition underlying the proposition is the following:



i) When the risk of a negative shock is so high that (31) holds, incentive problems generate an “innovation trap.” If effort was observable, it would be feasible to request high effort from all managers. This would enable investment to take place, which would, in turn, generate learning about the strength of the innovation. Because of moral hazard however, when the risk of a negative shock is high it is impossible to ensure that all managers exert high effort, therefore investment in the innovative sector is not profitable. So the innovation cannot develop, and learning cannot take place.

ii) When  $\theta_t$  is intermediate, while in the first best managers exerting low effort and managers exerting high effort would choose different contracts, under asymmetric information such sorting is not incentive compatible. Hence there is pooling. In line with the argument that led to Proposition 3, this pooling equilibrium cannot be undercut by raising managers’ success payments and reducing their failure payments so as to attract only good managers (the traditional cream skimming argument) because failure payments are zero and negative payments are precluded by managers’ limited liability.

## 4.2 Implications of binding incentive constraints

The next implication summarizes how moral hazard affects the development of innovations. In line with the above analysis, we focus on the case where  $\theta_t$  is large and (18) holds. Part i) of Proposition 5 implies that when initial confidence is very low, as  $\theta_0 > \frac{1}{\mu+x\Delta} \frac{Y-(1+r)}{Y}$ , and (18) holds, moral hazard precludes the development of innovations that would have occurred in the first best. This yields the following implication:

**Implication 7:** *When  $\theta_0 > \frac{1}{\mu+x\Delta} \frac{Y-(1+r)}{Y}$  a decline in the rate of return on standard investments ( $r$ ) can trigger a wave of innovations.*

When  $r$  declines, the threshold level above which innovations are trapped goes up. Hence, innovations that had become available but had not been able to develop can suddenly get implemented. Thus, there is a wave of innovations.

Now turn to part ii) of Proposition 4 and its illustration in Figure 4. Comparing the slopes of the lines in Figure 4, and reasoning as for Implication 1, we see that when effort is unobservable and  $\theta \in [\hat{\theta}, \frac{Y-(1+r)}{(\mu+\Delta x)Y}]$ , the rate of growth of the innovative sector is larger than in the first best. This reflects that many managers enter and exert low effort, in contrast with the first best where only efficient managers, exerting high effort, would enter.

That moral hazard spurs the entry of inefficient managers can lead to a situation where the size of the innovative sector is larger than in the first best.<sup>21</sup> To see how this obtains, consider Figure 4. Managers that are hired and exert low effort are those with  $C_i$  in  $[\underline{C}, \bar{C}]$ . As illustrated in Figure 4, the  $\bar{C}$  line intersects the horizontal axis at  $\theta_t = \frac{1}{\mu+x\Delta} \frac{Y-(1+r)}{Y}$ , which is larger than the point at which  $\gamma_t$  intersects the horizontal axis,  $\theta_t = \frac{1}{\mu+\Delta} \frac{Y-(1+r)}{Y}$ , but lower than the point at which  $\alpha_t$  intersects the horizontal axis. On the other hand,  $\bar{C}$  intersects  $\gamma_t$  for  $\theta_t = \frac{Y-(1+r)}{Y}$ , a point at which  $\gamma_t > \alpha_t$ . Hence, there exists a threshold  $\theta^* \in [\frac{Y-(1+r)}{Y}, \frac{1}{\mu+x\Delta} \frac{Y-(1+r)}{Y}]$ , such that  $\bar{C} > \max[\alpha_t, \gamma_t]$  for  $\theta_t \in [\frac{Y-(1+r)}{Y}, \theta^*]$ . Now, in this region, the size of the innovative sector in the first best is  $F(\max[\alpha_t, \gamma_t])$ , while in the second best it is  $F(\bar{C})$ . Hence, for these values of  $\theta_t$ , the size of the innovative sector is larger under moral hazard than in the first best. The next implication summarizes the above discussion.

**Implication 8:** *Under moral hazard, when (18) holds, if the innovation is not trapped, the growth rate of the innovative sector is strictly larger than in the first best, as long as  $\theta_t > \hat{\theta}$ . Further-*

<sup>21</sup>This is reminiscent of the overinvestment result of De Meza and Webb (1987).

more, there exists a threshold  $\theta^* \in [\frac{Y-(1+r)}{Y}, \frac{1}{\mu+x\Delta} \frac{Y-(1+r)}{Y})$ , such that, for  $\theta_t \in [\frac{Y-(1+r)}{Y}, \theta^*)$ , the size of the innovative sector is larger than in the first best.

The intuitive economic reason why moral hazard inflates the innovative sector is that, as mentioned above, it spurs the entry of managers exerting low effort. This fuels the growth of the sector. On the other hand, it lowers the average expected surplus generated by investments in the innovative sector. One could think this decline in expected surplus would deter investment by principals. This is not the case because, in the pooling equilibrium of Proposition 4, there is cross-subsidization of managers exerting low effort by managers exerting high effort. The former receive higher expected compensation than the (negative) surplus they generate for society, i.e., they earn rents. In contrast, the managers exerting high effort receive lower expected compensation than the (positive) surplus they generate for society. Hence, the expected losses incurred by investors hiring managers who turn out to exert low effort are offset by their expected gains when hiring managers who turn out exerting high effort. Thus, in a sense, the excessively inflated growth of the innovative sector is funded by the subsidies of the managers exerting high effort. And these subsidies result in agency rents for managers exerting low effort, as stated in the next implication.

**Implication 9:** *Under moral hazard, when (18) holds, for  $\theta_t \in [\frac{Y-(1+r)}{Y}, \theta^*)$ , agents exerting low effort earn agency rents.*

Taken together, Implications 8 and 9 contrast with previous theoretical results. To the extent that rents are transfers from principals to agents, they tend to deter investment by managers. In this context, moral hazard reduces the size of the sector relative to the first best, as, e.g., in Axelson and

Bond (2011). This is not the case in the present model, where, in contrast with Axelson and Bond (2011), not only effort but also the cost of effort are unobservable. In this context, the rents earned by inefficient agents are funded by the efficient agents, rather than the principals.

While the inflated growth of the innovative sector is privately optimal for the managers exerting low effort, who would not have been hired in the first best, it is socially costly: it drives expected utilitarian welfare below its first-best level, due to the value-destroying entry of managers exerting low effort. This social cost materializes when a negative shock hits and large losses are incurred due to lack of risk-prevention by low-effort managers. This is stated in the next implication.

**Implication 10:** *Under moral hazard, when (18) holds, for  $\theta \in [\frac{Y-(1+r)}{Y}, \theta^*)$ , default probabilities and aggregate losses in case of shock are higher than in the first best.*

## 5 Conclusion

Our analysis of the dynamics of innovations and risk under learning yields two key insights: First, the strongest growth episodes of the innovative sector are fueled by the entry of managers exerting low risk prevention effort – and therefore correspond to a decline in risk prevention standards. Second, under moral hazard, there is excessive entry of managers exerting low effort and earning informational rents, so that the innovative sector is larger and riskier than in the first best.

Thus, in our model, the signature of moral hazard is strong growth at early stages of the development of the innovation. In the first best, early growth is slow, because limited confidence implies only managers exerting high effort should enter. Under asymmetric information, early growth is strong, in

spite of limited confidence, due to the entry of managers exerting low prevention efforts, that can't be screened from those exerting high prevention effort.

While the present model features only managers and investors, it would be interesting to extend the analysis by introducing a supervisor or regulator, better able than investors to monitor the managers' risk-management systems. Since under asymmetric information there is excess entry of managers with inefficient risk-management systems, supervisory monitoring could improve welfare by imposing compliance to risk-management standards. When should that occur? Our theoretical analysis suggests that strong growth should not be taken as an encouraging sign that the innovation is healthy, calling for "light-touch regulation." Quite to the contrary, it is in periods of strong growth that resources should be spent to monitor the innovative sector, check risk-prevention standards, and bar entry for institutions with weak risk-management systems.

Also, while our results obtain with rational agents, they could be amplified by psychological biases, such as, e.g., overconfidence. After a few years without negative shocks, overconfident market participants would become excessively confident that the innovation is strong.<sup>22</sup> This would magnify the effects we analyze, reduce risk-prevention further, and make the innovative sector more vulnerable.

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<sup>22</sup>This is consistent with the approach taken in Daniel, Hirshleifer and Subrahmanyam (1998) or Gervais and Odean (2001). In their models, however, agents overestimate the precision of *private* signals, while here they would overestimate the precision of *public* signals.

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### Appendix: Complement to the proof of Proposition 3

In the text we showed that, when  $\theta > [Y - (1 + r)] / Y$ , there cannot be two contracts in equilibrium, one inducing high effort only, the other inducing low effort only. We now show that the proof extends to rule out the situation where one of the two contracts would attract both managers exerting high effort and managers exerting low effort.

The proof proceeds by contradiction. Suppose there were two contracts:

- $m_{both}$  inducing low effort by a fraction  $x$  of the managers who choose it and high effort by the remaining fraction,
- and  $m_{high}$  inducing only high effort.

If one of these two contracts gave higher compensation for high effort than the other, then all managers exerting high effort would choose the former, and the latter would not attract any manager. Thus, for both contracts to attract managers exerting high effort, it must be that they give managers the same expected pay-off conditionally on  $e = 1$ , i.e.,

$$(1 - \theta)m_{both}(\xi = 0) + \theta(1 - \mu)m_{both}(\xi = 1) = (1 - \theta)m_{high}(\xi = 0) + \theta(1 - \mu)m_{high}(\xi = 1).$$

Moreover competition between investors implies they exactly break even for each of the two contracts, i.e.,

$$(1 - \theta)m_{high}(\xi = 0) + \theta(1 - \mu)m_{high}(\xi = 1) = (1 - \theta\mu)Y - (1 + r),$$

and

$$(1 - \theta)m_{both}(\xi = 0) + \theta(1 - \mu - \Delta x)m_{both}(\xi = 1) = (1 - \theta\mu - \theta\Delta x)Y - (1 + r).$$

Equality of expected transfers conditional on high effort along with the break-even condition for  $m_{high}$  imply

$$(1 - \theta)m_{both}(\xi = 0) + \theta(1 - \mu)m_{both}(\xi = 1) = (1 - \theta\mu)Y - (1 + r).$$

Subtracting from the break-even condition for  $m_{both}$ , this yields  $m_{both}(\xi = 1) = Y$ . Substituting  $m_{both}(\xi = 1) = Y$  into the break even condition for  $m_{both}$ , we have

$$m_{both}(\xi = 0) = Y - \frac{1 + r}{1 - \theta},$$

which contradicts the limited liability condition that  $m_{both}(\xi = 0) \geq 0$  when  $\theta > [Y - (1 + r)]/Y$ . Thus, when  $\theta > (Y - (1 + r))/Y$ , it cannot be the case, in equilibrium, that one contract attracts only managers exerting high effort while the other attracts both managers exerting high effort and managers exerting low effort. Reasoning along similar lines, one rules out the case where one contract attracts managers exerting low effort only, while the other attracts managers exerting high effort as well as managers exerting low effort.

Finally, we rule out the possibility that there would be two different contracts,  $m_1$  and  $m_2$ , each one attracting both managers exerting high effort and managers exerting low effort. For both contracts to attract managers exerting high effort it must be that

$$(1 - \theta)m_1(\xi = 0) + \theta(1 - \mu)m_1(\xi = 1) = (1 - \theta)m_2(\xi = 0) + \theta(1 - \mu)m_2(\xi = 1).$$

For both contracts to attract managers exerting low effort it must be that

$$(1 - \theta)m_1(\xi = 0) + \theta(1 - \mu - \Delta)m_1(\xi = 1) = (1 - \theta)m_2(\xi = 0) + \theta(1 - \mu - \Delta)m_2(\xi = 1).$$

Subtracting the latter equality from the former, we get  $m_1(\xi = 1) = m_2(\xi = 1)$ . Substituting, we get  $m_1(\xi = 0) = m_2(\xi = 0)$ . Hence we cannot have two different contracts, as stated in Proposition 3.

Figure 1: The structure of uncertainty in period  $t$

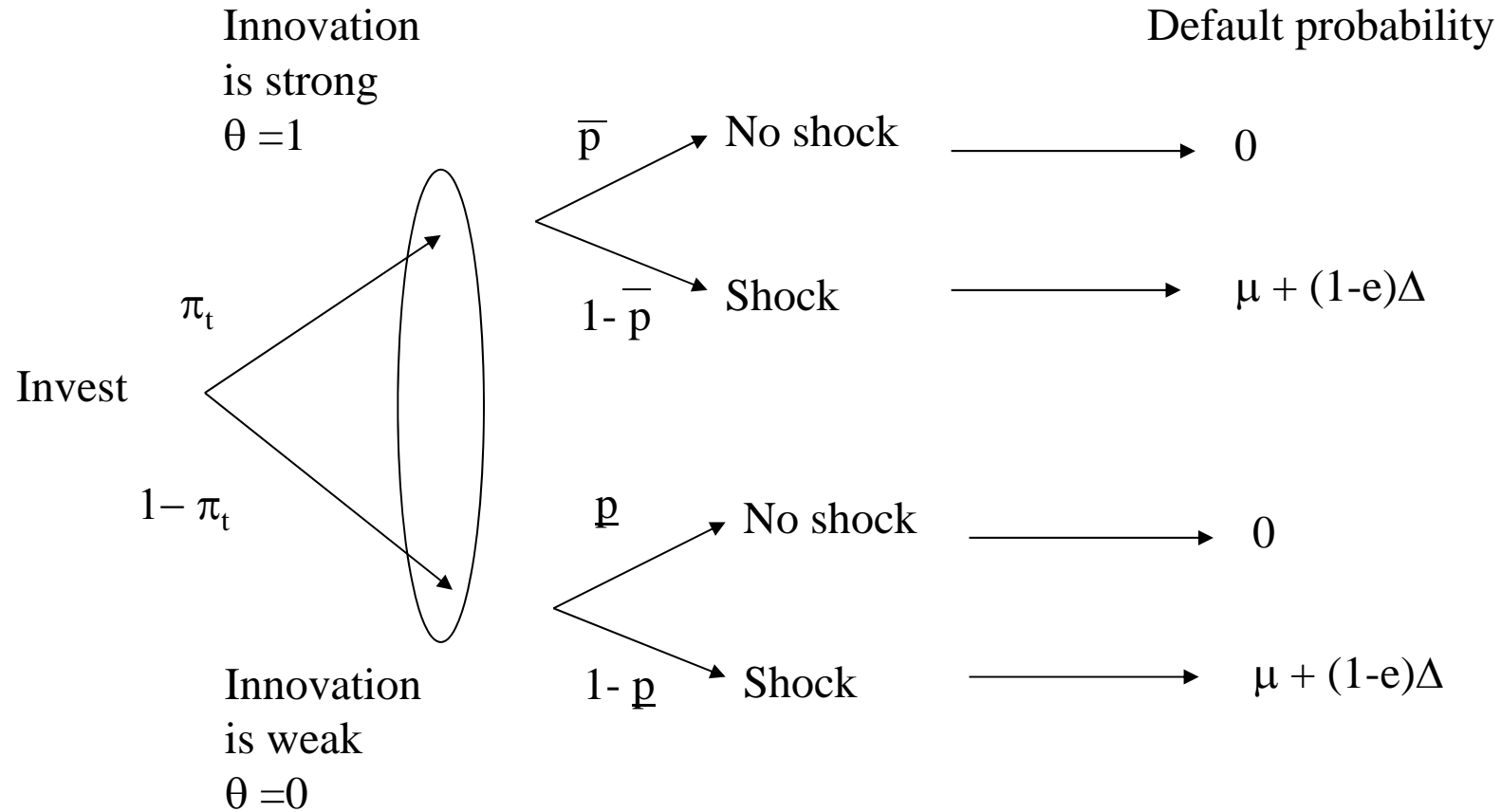
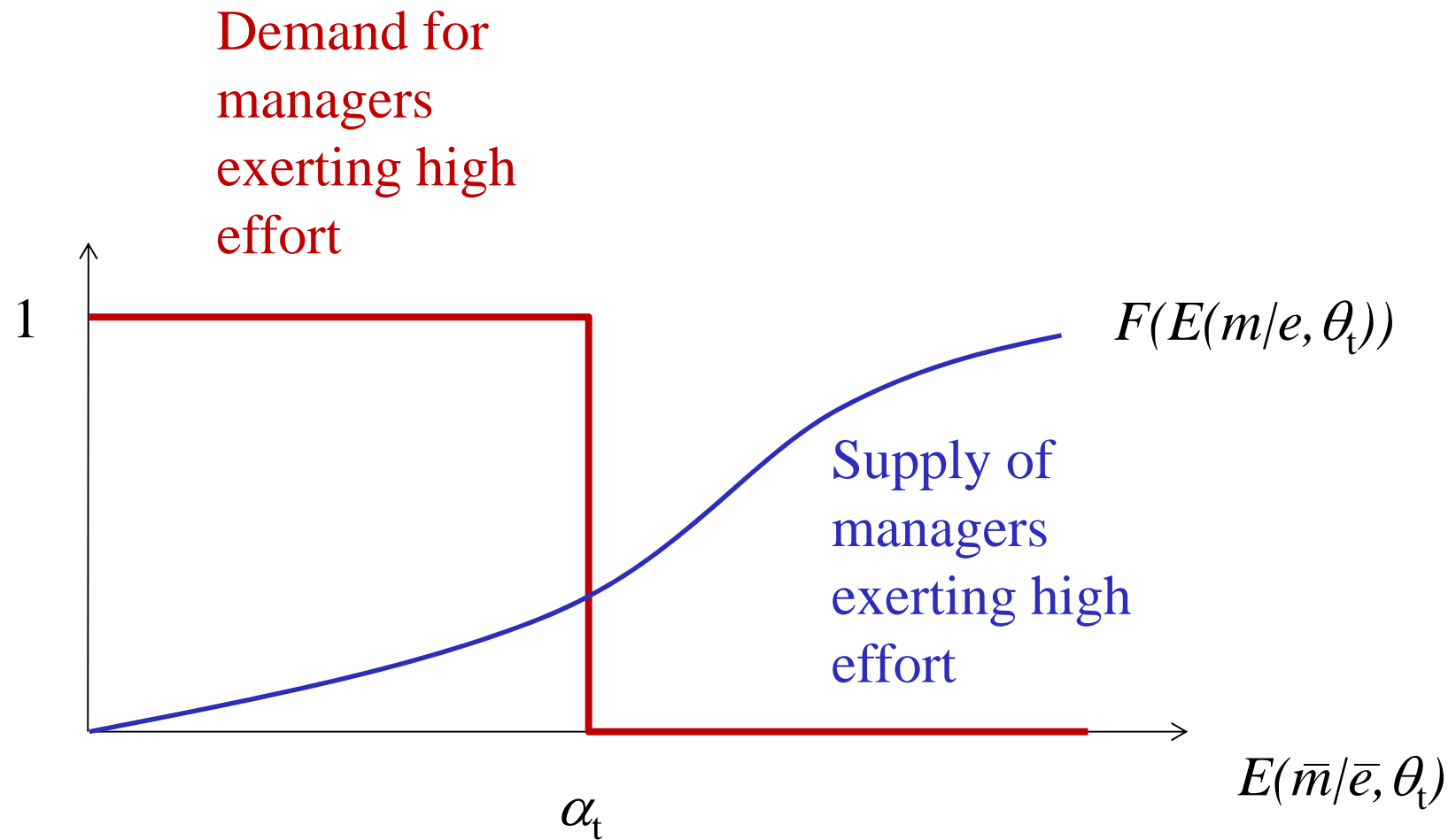


Figure 2: Market clearing when  $\alpha_t < \theta \Delta Y$



### Figure 3: Equilibrium dynamics without incentive problems

$\alpha$  is the expected surplus generated with high effort (gross of the cost of effort)

$\beta$  is the threshold value of  $C$  below which high effort is preferred to low effort

$\gamma$  is the threshold value of  $C$  below which delegated investment with low effort is more valuable than self investment. When  $C_i \leq \min[\alpha, \beta]$  there is high effort.

When  $\beta < C_i < \gamma$  there is low effort.

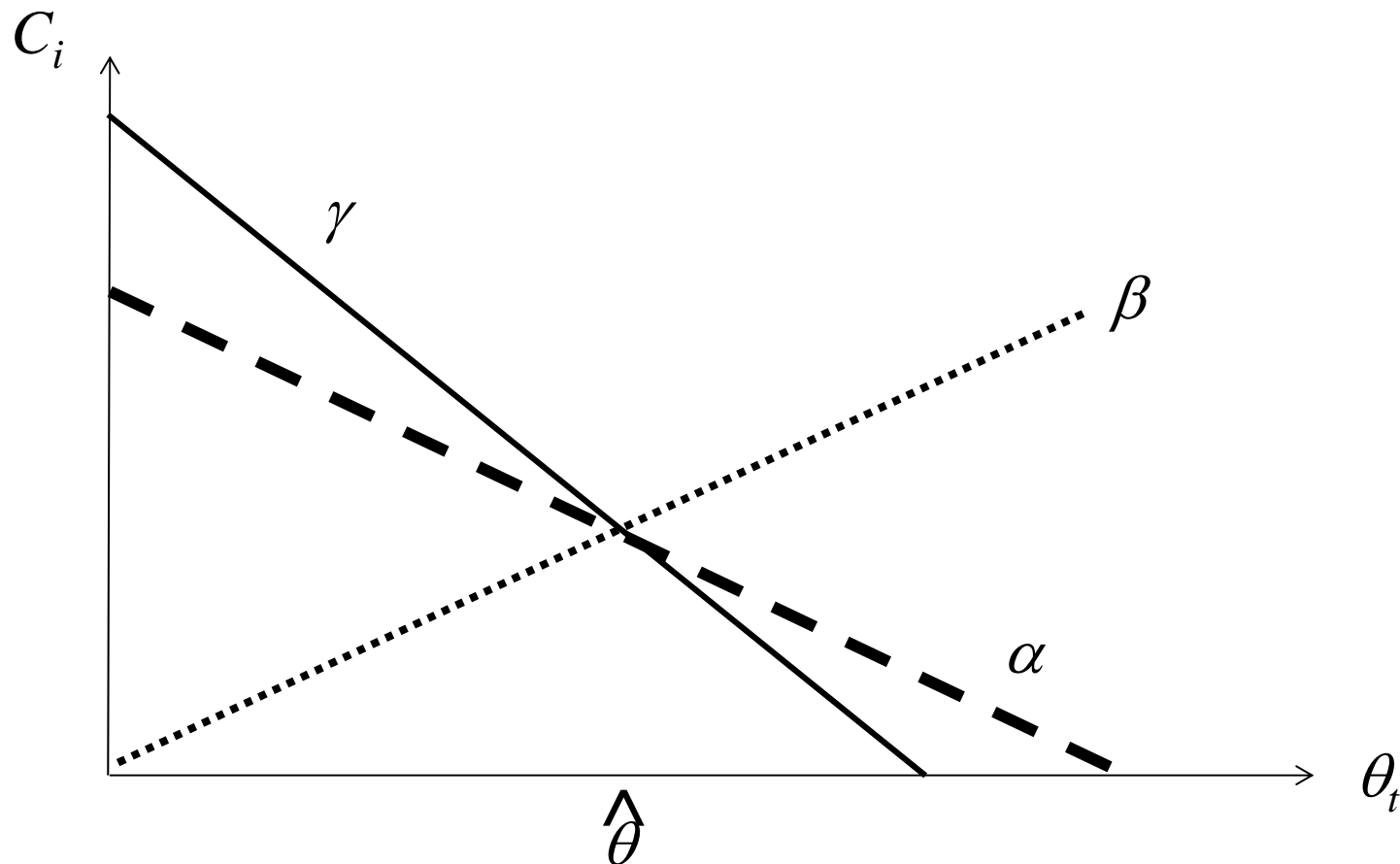


Figure 4: Equilibrium under moral hazard when  $\Delta/(1-\mu) < 1 - \underline{e}$

$\alpha$ ,  $\beta$  and  $\gamma$  are as in Figure 3. For  $\theta \geq (Y-(1+r))/Y$ , when  $C_i \leq \underline{C}$  there is high effort. When  $\underline{C} < C_i < \bar{C}$  there is low effort. For  $\theta < (Y-(1+r))/Y$ , when  $C_i \leq \beta$  there is high effort, when  $\beta < C_i < \gamma$  there is low effort.

