Innovation, Spillovers, and Organizational Change

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Abstract

How do organizations respond to technological shocks? This paper studies how technological shocks to a division's expected productivity of innovation affect organizational change. Key ingredients are the presence of cross-divisional spillovers, strategic communication within the organization, and the risk-return trade-off associated with innovation. When the importance of spillovers is moderate and decentralization is optimal, a technological shock that increases the productivity gap across divisions can induce a shift from decentralized to centralized innovation. Centralization: *i*) helps to curb the innovative ambitions of the manager of the most productive division, which hurt spillovers; and *ii*) improves communication within the organization.

Keywords: Innovation, Cheap Talk, Centralization, Organizational Change, Technological Shock

JEL code: D23, L23, O31

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1 Introduction

Technological shocks may affect the dynamics of entire industries and, in turn, how firms allocate decision-making authority. For instance, the introduction of Apple's iPhone in 2007 changed the future of Nokia's mobile phone division which had been among the most successful and innovative mobile phone manufacturers in the world. After several years of disappointing performance, Nokia hired a new CEO, Stephen Elop. The new CEO restructured the company and provided division managers with higher decision-making authority to allow for better local responsiveness.[1] Similarly, the success of the personal computer in the early 1980's changed the future of IBM's PC division, which initially had been quite independent from the rest of the organization. IBM reacted in the opposite way to Nokia by centralizing authority.

This paper develops a model to study how organizations respond to technological shocks in the presence of cross-divisional spillovers. The organization must decide which new technologies to adopt, if any, in each division. Innovation involves the simultaneous choice of a vector of technologies where each technology is taken from the positive real half-line. Each technology generates a stochastic outcome. Absent spillovers, the adoption of a new technology involves the trade-off between increasing the *profitability* of a division, through innovation that is division-specific, and the associated *risk* of innovation. The presence of cross-divisional spillovers generates a three-way trade-off because the organization needs to consider how innovation will affect technological exchanges, or generate technological incompatibilities, across divisions. In this case, the allocation of authority over innovation decisions can significantly affect organizational performance through the technologies that are adopted and the incentives that division managers have to share information.

The baseline model considers a centralized organization which consists of a corporate headquarters office and two divisions that differ in the expected productivity of new technologies. The headquarters (HQ) manager cares about total profits, whereas division managers care only about their own division's profits.[2] Authority over innovation in each division resides at the top. However, division managers privately observe the *riskiness* of innovation in their own division. Before any decisions are made, division managers can communicate their private information to the HQ manager. I assume that the HQ manager cannot commit to transfers contingent on the information that she receives so that communication is informal,

[1] See Andrew Hill's article "Inside Nokia: trying to revive a giant." *The Financial Times*, April 11, 2011.

[2] The bias may be less than extreme as long as division managers are sufficiently biased in favor of the profitability of their own division.

that is, *cheap-talk*.[3]

I first show how technological asymmetries and the presence of spillovers may distort the incentives that division managers have to communicate with headquarters: Communication might be informative with both division managers, only one manager, or being completely uninformative depending on the importance of spillovers. Centralized authority induces each division manager to understate the riskiness of innovation in his division in order to induce more innovation from the HQ manager who has a higher concern for spillovers. In particular, the division manager of the most productive division perceives the underinvestment in innovation as more severe because he cares less about spillovers and more about the profitability of his own division. This implies that that division manager will have a relatively higher incentive to misreport which leads to a relatively lower equilibrium quality of vertical communication compared to the least productive division. When the importance of spillovers is small this bias affects the quality of communication but informative communication is feasible with both division managers. As the importance of spillovers increases, only the manager of the least productive division will be able to credibly transmit information whereas the other manager will be babbling. Ultimately, informative communication will be infeasible within the organization when the importance of spillovers is sufficiently high.

A technological shock that increases the productivity gap between divisions decreases the quality of vertical communication with the most productive division whereas it improves communication with the least productive division. The reason for the worsening of communication between the manager of the most productive division and headquarters follows from the logic of the previous paragraph. Perhaps more interesting is the fact that a technological shock that leaves the prospects of innovation unaffected in the least productive division can induce the manager of that division to communicate more with headquarters. This effect stems from the presence of spillovers. As innovation in the least productive division is relatively less appealing to the manager of that division, he perceives spillovers as more important for the profitability of his own division. Thus, a shock that further increases productivity in the most productive division also represents a threat for expected spillovers in the least productive division which induces the manager of that division to be more cooperative with headquarters.

If division managers had full control over innovation in their own divisions (i.e., decentralization), no informative, horizontal, communication would occur in equilibrium between

[3] In this regard, I follow the property rights literature as in Grossman and Hart (1986) and Hart and Moore (1990) but, in line with the recent literature (see, e.g., Alonso, Dessein, and Matouschek 2008), I also assume that decisions are contractible neither ex-ante nor ex-post.

the division managers, regardless of the importance of spillovers. Unlike the case of centralized innovation, division managers have an extreme incentive to exaggerate the riskiness of their divisions when they communicate with each other.[4] Communicating a high riskiness, if believed, is used by a division manager as an indirect signal to make the other manager believe that he will not choose a very innovative technology. As the other division manager then believes spillovers to be higher in expectation (due to the lower chance of technological incompatibilities), he will also reduce the level of innovation in his own division to foster spillovers even further. In principle, the division manager might increase rather than decrease innovation but this is suboptimal as a way to increase profitability because more innovation also brings higher risk whereas fostering spillovers is less risky. As the misreporting division manager would be able to increase expected profits in his division, no informative communication could occur.

These insights lead to the main result of the paper about organizational change: As long as the importance of spillovers is moderate (that is, not too large), a positive technological shock that increases the productivity gap across divisions can induce an organizational shift from decentralization to centralization. In this scenario, centralizing authority can increase expected organizational performance by: *i*) curbing innovation in the most productive division, which enhances spillovers and reduces the volatility of profits; and *ii*) fostering more communication within the organization. A technological shock changes the risk-return trade-off faced by the manager of the division hit by the shock. Whereas that manager might either increase or decrease innovation in his own division depending on the size of the shock, his behavior is perceived as too risky compared to what the HQ manager what do in response to the same shock. The shock also makes expected spillovers more sensitive to innovation performed within the division hit by the shock, because it makes innovation even more division-specific, and thus less likely to generate positive spillovers for the other division. As spillovers are now relatively more sensitive to innovation, communication becomes more important to ensure proper coordination. However, internal communication is better achieved through centralization.

When the absolute importance of spillovers is large (but not too large to prevent innovation), a similar technological shock reduces the attractiveness of centralization. The equilibrium technologies are more sensitive to technological shocks when spillovers are large because innovation has a higher impact on organizational performance. Furthermore, large

[4] The fact that horizontal communication can be less informative than vertical communication was already known from the analysis in Alonso, Dessein, and Matouschek (2008) and Rantakari (2008). In this model, however, the result is extreme.

spillovers are already associated with a low quality of vertical communication because division managers have higher incentives to misreport. As a positive technological shock will decrease the quality of communication even further precisely when information is most needed, the organization may find decentralization more appealing than centralization after the shock because decentralization guarantees an optimal use of information. However, the sheer importance of spillovers and thus the need for coordination may counteract even a large technological shock.

1.1 Contributions to the literature

The first contribution of the paper is a framework that allows to study innovation in organizations by formalizing the three way trade-off between increasing the expected profitability of an organization, limiting the risks of innovation, and fostering technological spillovers across divisions. This is achieved through the application of modeling techniques recently applied in the literature on experimentation and multi-armed bandit models. The main building block is represented by the elegant, probabilistic learning model introduced by Callander (2011) that allows for a clear characterization of the three-way trade-off as well as a closed-form solution of the model. However, I focus attention on the study of innovation within organizations in which information about key aspects of the payoff distributions is dispersed. I also allow for strategic information transmission about relevant characteristics of the environment in the form of cheap-talk.

This paper also contributes to the literature on organizational design. The literature is quite vast, so I limit attention to a brief overview of the articles that are most relevant for this paper. My analysis builds on the recent contributions by Alonso, Dessein, and Matouschek (2008) (ADM), and Rantakari (2008) that study the trade-off between coordination and adaptation in organizations.[5] ADM show that decentralization of authority can be optimal even when the organization's need for coordination is very large provided that division managers' incentives are sufficiently aligned. Rantakari focuses instead on how asymmetries in the size and need for coordination of each division affect the optimal allocation of authority. I take a different perspective and analyze how technological shocks to a division's productivity may affect the risk-return trade-off faced by each division in the presence of cross-divisional

[5]See also Dessein and Santos (2006) for a team-theoretic approach. Alonso (2008) instead develops a model with two interdependent activities, as in this paper, and studies how control sharing between a principal and an informed agent affects the quality of communication. Sharing control is optimal provided that activities are complementary to each other. Although in this paper innovation decisions are also interdependent, they involve two separate divisions so that each division manager only knows the local conditions of her own division.

spillovers. I thus investigate a possible mechanism through which shocks may propagate within an organization and determine organizational change, while maintaining symmetry about size and individual coordination needs. This approach generates new insights about how technological asymmetries affect internal communication and, in turn, organizational performance. These effects have not been explored in previous models.[6]

This paper also contributes to the literature on strategic communication. I extend the classic framework of Crawford and Sobel (1982) to environments in which multiple senders have private information about the variance parameters of mutually independent Brownian motions, which could also be relevant for other applications. Unlike in Crawford and Sobel, partition equilibria are affected by the importance of spillovers and technological asymmetries between the two divisions. I further study how technological shocks affect the quality of communication within the organization.[7]

Finally, Qian, Roland, and Xu (2006) study experimentation with uncertain projects (i.e., ideas) that arrive over time and whose adoption could potentially improve firm's profits. In particular, they compare the performance of the M-form and the U-form and find that the M-form can promote innovation through more flexibility in experimentation. In contrast, I fix the organizational structure (i.e., M-form) and vary the allocation of authority. I focus attention on how technological shocks affect strategic information transmission within the organization. Finally, I add a spatial dimension to innovation that allows an agent to choose more or less innovative technologies, whereas in Qian, Roland, and Xu experimentation can only be small-scale (i.e., adopted in only one division) or full-scale (i.e., adopted by the entire organization).

2 Model

I study innovation in a multi-divisional organization which consists of two division managers (D1 and D2, *"he"*), and one headquarters manager (HQ, *"she"*). The organization must

[6] Other papers in the literature have explored the relative efficiency of horizontal coordination and hierarchical (i.e., vertical) control (see, e.g., Aoki 1986), the optimal allocation of formal versus real authority to an agent and how this, in turn, affects the agent's incentive to acquire information (Aghion and Tirole 1997), how providing incentives for effort provision interacts with efficient decision making or affects communication (Athey and Roberts 2001, Dessein, Garicano, and Gertner 2010, Friebel and Raith 2010).

[7] Different lines of research have investigated information processing in organizations (e.g., Marshak and Radner 1972, Radner 1993, Bolton and Dewatripont 1994, Van Zandt 1999, Vayanos 2003), how the trade-off between acquiring and communicating knowledge affects organizational design (e.g., Garicano 2000), or the scope of language (i.e., specialized versus vague) within organizations (e.g., Crémer, Garicano, and Prat 2007).

simultaneously choose a technology $x_i \in \mathbb{R}_+$ in each division which generates an outcome $f_i(x_i) \in \mathbb{R}$, $i = 1, 2$. The outcome functions, $f_i(\cdot)$ $i = 1, 2$, are unknown except at the origin where $f_i(0) > 0$, which represents the outcome associated with the technology currently in use in division i.

Innovation in multi-divisional organizations that share spillovers faces the three-way trade-off between increasing the expected profitability of the organization, limiting the risks associated with innovation, and fostering spillovers across divisions. I capture this trade-off through the specification of the profit functions and the uncertainty regarding the mappings between technologies and outcomes. In particular, for a pair of technologies (x_i, x_j) with associated outcomes $(f_i(x_i), f_j(x_j))$, the profits of division i are given by

$$\pi_i^{\gamma}\left(f_i(x_i), f_j(x_j)\right) = -[f_i(x_i)]^2 + \gamma f_i(x_i) f_j(x_j), \quad i = 1, 2 \tag{1}$$

The first term captures the possible inefficiency that is generated from the use of a technology x_i. Outcomes closer to zero are associated with more profitable technologies.[8] The second term captures the effect on profits derived from cross-divisional, technological spillovers generated by the innovative efforts of each division. The parameter $\gamma \geq 0$ measures the (absolute) importance of technological spillovers over divisional profitability.[9] Technological spillovers could be either positive or negative, for example when the technologies adopted by each division turn out to be, respectively, compatible or incompatible with each other.

I know specify the source of uncertainty that characterizes the outcome functions. All players share the common belief that the outcome functions are the realized paths of two independent Brownian motions.[10] The two Brownian motions have drifts $\mu_1 < 0$ and $\mu_2 < 0$, respectively, which are common knowledge. I refer to $|\mu_i|$ as the expected *productivity* of innovation in division i. Each division manager privately observes the variance parameter, $\sigma_i^2 > 0$, specific to his own division. I refer to the parameter σ_i^2 as the *riskiness* of division i. It is also common knowledge that σ_1^2 and σ_2^2 are independently and uniformly distributed on the intervals $[a_1, b_1]$ and $[a_2, b_2]$, respectively, with $0 < a_1 < b_1$ and $0 < a_2 < b_2$. Figure 1 shows two possible realizations of the outcome functions.

Brownian uncertainty implies that, for any $x_i > 0$, $f_i(x_i)$ is normally distributed with

[8]This specification is a generalization of the usual quadratic-loss function which is common to many cheap-talk models.

[9]In order to solve the model, I will introduce an upper bound on the size of γ when I analyze the communication subgame.

[10]As any stochastic process, Brownian motion can be thought of as a probability distribution over sample paths/outcome functions. This specification of uncertainty was first introduced by Jovanovic and Rob (1990).

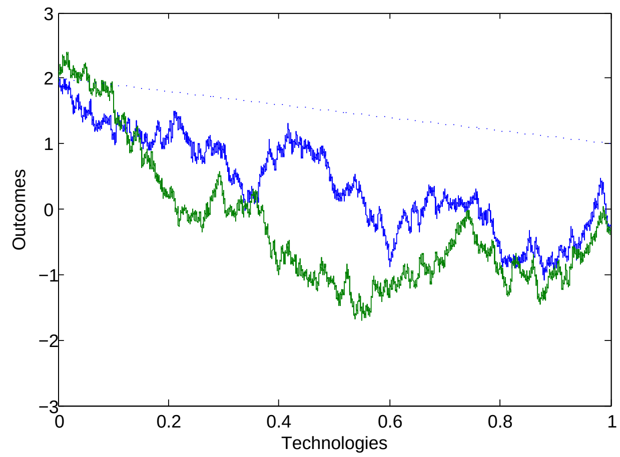

Figure 1: Realized paths of two independent Brownian motions with $f(0) = 2$, $\mu_i = \mu_j = -1$ and $\sigma_i^2 = \sigma_j^2 = 2$.

mean $f_i(0)+\mu_i x_i$, and variance $\sigma_i^2 x_i$.[11] Thus, given a pair of technologies (x_i, x_j) and riskiness parameter σ_i^2, the expected profits of division i can be written as, for $i = 1, 2$,

$$E\left[\pi_i^{\gamma}\left(f_i(x_i), f_j(x_j)\right)|x_i, x_j, \sigma_i^2\right] = -\left(f_i(0) + \mu_i x_i\right)^2 - \sigma_i^2 x_i + \gamma\left(f_i(0) + \mu_i x_i\right)\left(f_j(0) + \mu_j x_j\right) \tag{2}$$

I define $\bar{\sigma}_i^2 \equiv E[\sigma_i^2]$ and I assume that $f_1(0) = f_2(0) \equiv f(0)$.[12] Finally, I call the ratio $\left|\frac{\mu_i}{\mu_j}\right|$ the *productivity gap* between division i and division j.

This framework captures the three-way trade-off mentioned at the beginning of the section. Starting from the status quo technologies, $(0, 0)$, innovation with a pair of technologies (x_i, x_j) affects the expected profits of each division through the expected productivity and the riskiness associated with those technologies, and the size of expected cross-divisional spillovers. In particular, the negative drift implies that moving away from the status quo technologies generates expected outcomes closer to zero and is thus associated with technologies that are more productive, in expectation. However, more productive technologies are also riskier. Thus, a new technology bears the risk of being ex-post less productive than the one currently used and it also incurs the risk of generating negative spillovers which reduce profitability.

[11]Clearly other specifications of uncertainty would be plausible. However, Brownian uncertainty captures the most important characteristics of the payoff distribution in a parsimonious way and it allows for closed form solutions.

[12]This assumption can be relaxed but it makes the analysis more transparent as the only source of technological asymmetries is given by the drift parameters.

As far as technological spillovers are concerned, I notice three observations. First, technological spillovers are high in expectation when the status quo technologies are implemented. This is because the status quo technologies are technologies which the members of the organization are already very familiar with. Second, expected technological spillovers are initially decreasing in the size of the innovations undertaken. Third, a change in the expected productivity of innovation in division i (i.e., μ_i) affects the sensitivity of expected spillovers to innovation in that division. The interpretation of the last two observations is that innovation is division-specific and it is thus possible that innovation may reduce technological compatibility between divisions within the organization. However, if both divisions choose very large technologies, it is also more likely that the divisions may discover technologies that can generate positive spillovers for the organization.[13]

I illustrate the framework through the context of a real life example.[14] In the mid 1980's, IBM was facing the organizational challenge of coordinating its mainframe division (M) with innovation in the newer personal computer division (PC). The PC division was less established and offered comparatively more opportunities for innovation than the mainframe division due to the lack of a standard platform for personal computers at that time. At the same time, innovation was also riskier for personal computers exactly because of the lack of a common platform. This type of situation can be captured through a parametrization such that $\bar{\sigma}_M^2 < \bar{\sigma}_{PC}^2$ and $|\mu_M| < |\mu_{PC}|$. This parametrization also captures the idea that innovation in the PC division is more likely to generate lower spillovers for the organization. This was the case at IBM where senior managers were concerned that the products of the new division would have cannibalized sales of other products.

I assume that authority over the innovation decisions is centralized.[15] The HQ manager has the right to choose any technology. As information about the riskiness of innovation is dispersed within the organization, I allow the division managers to communicate with headquarters before any technology is chosen but, as in Alonso, Dessein, and Matouschek (2008) and Rantakari (2008), the HQ manager cannot commit to transfers based on the information received. Thus, communication is *cheap-talk* and each division manager simultaneously sends a message $m_i \in M_i$, $i = 1, 2$, where $m \equiv (m_1, m_2)$.

Each division manager maximizes profits in his own division, whereas the HQ manager maximizes total firm's profits, $\pi_1^\gamma + \pi_2^\gamma$. Thus, the HQ manager has no preference for any particular division but cares only about the interests of the organization.

[13]As I will show, it is never optimal for the organization to choose very large technologies given the very large variance associated with those technologies, as long as the importance of spillovers is bounded.

[14]The following discussion is based on Bresnahan, Greenstein, and Henderson (2007).

[15]In Section 4, I consider the case in which authority is decentralized.

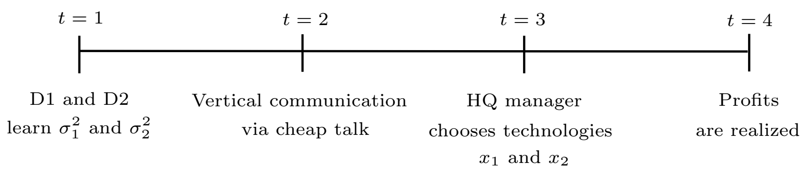

Figure 2: Timing of the game.

The timing of events is as follows. First, each division manager learns the riskiness of his own division. Second, division managers send messages simultaneously. Given the information received from the division managers, the HQ manager chooses a vector of technologies. Finally, profits are realized. Figure 2 summarizes the timing of the game.

I solve for the Perfect Bayesian equilibria (PBE) of the game. In the communication subgame, a PBE is characterized by communication rules for each division manager, decision rules and belief functions for the HQ manager, such that: *i*) the decision rules are optimal given the belief functions; *ii*) the communication rules are optimal given the decision rules; and *iii*) the belief functions are consistent with the communication rules and Bayes' rule whenever possible.

3 Innovation in Centralized Organizations

I start the analysis by considering the case in which there are no spillovers between divisions, that is, $\gamma = 0$.[16] Without spillovers, there is perfect alignment of interests between the division managers and the HQ manager. Even though the HQ manager still relies on information transmitted by the division managers, there exists an equilibrium in which truthful communication occurs. From now on, I focus on that equilibrium. When $\gamma = 0$, the equilibrium technologies are given by,[17]

$$x_i^0(\sigma_i^2) = \begin{cases} -\frac{f(0)}{\mu_i} - \frac{\sigma_i^2}{2\mu_i^2} > 0 & \text{if } f(0) > -\frac{\sigma_i^2}{2\mu_i} \\ 0 & \text{otherwise} \end{cases} \qquad i = 1, 2. \tag{3}$$

The HQ manager faces a trade-off between profitability and risk in each division. Moving away from the status quo technologies increases the expected profits of a division (given

[16] In this case, my analysis nests that of Callander (2011).

[17] Note that $\frac{dE\left[-(f_i(x_i))^2\right]}{dx_i}\Big|_{x_i=0} = -2\mu_i f(0) - \sigma_i^2$ which is positive provided that $f(0) > -\frac{\sigma_i^2}{2\mu_i}$. Given that $\frac{d^2E\left[-(f_i(x_i))^2\right]}{dx_i^2} = -2\mu_i^2 < 0$, the first-order condition is necessary and sufficient for an interior maximum.

$\mu_i < 0$) but it increases the variance of technologies at a rate equal to σ_i^2. Higher riskiness induces less innovation and possibly no innovation at all. The effect of an increase in the drift, $|\mu_i|$, is more complex because it depends on the absolute size of the drift. This is due to risk aversion. An increase in $|\mu_i|$ makes each technology close to the status quo closer to zero in expectation and thus more productive. This might suggest that more innovation should be undertaken, but innovation is also risky. Thus, following an increase in $|\mu_i|$, the optimal technology choice might trade off risk for a lower level of innovation because of the now higher associated expected outcome. However, an increase in $|\mu_i|$ unambiguously increases the expected profits of division i when the equilibrium technologies are strictly positive.[18]

To restrict attention to the interesting cases, I make the following assumption.

Assumption 1. $f(0) > -\frac{b_i}{2\mu_i}$, $i = 1, 2$.

Assumption 1 simply guarantees that the optimal technologies are strictly positive in both divisions when there are no spillovers.

3.1 Equilibrium technologies

The HQ manager can perfectly rank technologies according to their expected productivity but she is unsure of the riskiness of the technologies she chooses. Thus, she must rely on the information transmitted by the division managers. The HQ manager simultaneously chooses a vector of technologies to maximize total expected profits given the available information.

Let $\nu_i \equiv E_{HQ}[\sigma_i^2|m]$ denote the posterior expectation about σ_i^2 held by the HQ manager after receiving message m.[19] Proposition 1 characterizes the optimal technologies chosen by the HQ manager after vertical communication has taken place.[20]

Proposition 1 (Centralized Innovation). *Suppose that* $\frac{\nu_i}{\mu_i} \geq \frac{\nu_j}{\mu_j}$ *and* $\gamma < 1$. *Then,*

1. *If* γ *is small, the optimal technologies are both positive and given by*

$$x_i^C(\nu_i, \nu_j) = -\frac{f(0)}{\mu_i} - \frac{1}{1-\gamma^2}\frac{\nu_i}{2\mu_i^2} - \frac{\gamma}{1-\gamma^2}\frac{\nu_j}{2\mu_i\mu_j},\ i = 1, 2,\ i \neq j \tag{4}$$

2. *If* γ *is in an intermediate range, then the optimal technologies are* $x_j^C(\nu_j, \nu_i) = 0$ *and* $x_i^C(\nu_i, \nu_j) = -(1-\gamma)\frac{f(0)}{\mu_i} - \frac{\nu_i}{2\mu_i^2} > 0$.[21]

[18] To see this, note that $E[\pi_i^0|\sigma_i^2] = -\sigma_i^2\frac{f(0)}{|\mu_i|} + \frac{(\sigma_i^2)^2}{4\mu_i^2}$ and $\frac{\partial E[\pi_i^0|\sigma_i^2]}{\partial|\mu_i|} = \frac{\sigma_i^2}{\mu_i^2}\left(f(0) - \frac{\sigma_i^2}{2|\mu_i|}\right) > 0$ if $f(0) > \frac{\sigma_i^2}{2|\mu_i|}$.

[19] Note that message m_i only contains information about σ_i^2.

[20] The statement of the proposition is purposely informal for expositional reasons. A formal statement is contained in the Appendix.

[21] If $\frac{\nu_i}{\mu_i} = \frac{\nu_j}{\mu_j}$, the intermediate region disappears.

3. If γ is large, then the HQ manager avoids innovation in both divisions.

When both technologies are positive, the optimal technology x_i^C, $i = 1, 2$, is

(i) decreasing in γ, ν_i, ν_j, and increasing in $|\mu_j|$;

(ii) increasing in $|\mu_i|$ if, and only if,

$$|\mu_i| < \frac{\nu_i}{(1-\gamma^2) f(0) - \gamma \frac{\nu_j}{2|\mu_j|}}. \tag{5}$$

The HQ manager innovates in both divisions provided that the importance of spillovers is moderate. She instead avoids innovation when spillovers are sufficiently important for organizational performance because innovation, even if it increases the profitability of a division, reduces overall profitability through its effect on cross-divisional spillovers. The HQ manager could potentially generate large spillovers by choosing large technologies in each division but this would come at the cost of a very high variance in the underlying outcomes of innovation. As the importance of spillovers is bounded above, such behavior is suboptimal.

In an intermediate range, the HQ manager innovates only in the division which she considers the most attractive in terms of productivity and riskiness considerations. For instance, if the two divisions had the same drift, the HQ manager would prefer the division for which she holds the lowest posterior expectation about riskiness. If instead the HQ manager held the same posterior expectation about the riskiness of each division, she would prefer the division with the highest productivity.

An increase in the importance of spillovers or the posterior expectation about the riskiness of any division reduces the amount of innovation in all divisions. These comparative statics observations conform to what one would expect. As larger innovations have an initial negative effect on spillovers, the HQ manager will innovate less as γ increases. Similarly, when innovation in one division is perceived as riskier, this depresses the HQ manager's incentive to innovate in that division. Perhaps less immediately obvious, an increase in the perceived riskiness of division j also reduces innovation in division i. This effect stems from the fact that less innovation in division j increases the marginal value of increasing profitability in division i by exploiting spillovers rather than choosing a larger technology because spillovers involve less risk. This implies that the HQ manager prefers less innovation in division i as well, even though neither the productivity nor the riskiness of innovation have changed in that division.

A technological shock that increases the expected productivity of innovation in one division increases innovation in that division only if productivity was initially small, whereas it always increases innovation in the other division. Suppose that $|\mu_i|$ increases. The HQ manager unambiguously increases innovation in division j because the shock reduced the marginal benefit of spillovers which stimulates innovation in the division not hit by the shock. On the other hand, the interaction between expected productivity and risk can push innovation in division i in either direction. Proposition 1 shows that risk considerations dominate when the division is initially quite productive.

Proposition 1 also shows that the equilibrium technologies depend on the vector of posterior expectations which, in turn, depend on the messages sent by the division managers. This makes the analysis of the communication subgame that I shall discuss in the next subsection potentially quite complex. A division manager needs to assess the likelihood that his report will induce a posterior expectation which is higher than the one induced by the other division manager because the HQ manager might avoid innovation in his division. To avoid the complexities induced by those corner cases while still capturing the interesting strategic interactions underlying the model, I derive a uniform upper bound on the value of γ that insures that, for a given status quo outcome $f(0)$, the optimal technologies in (4) are strictly positive regardless of the posterior expectations held by the HQ manager. Note that $x_i^C(\nu_i, \nu_j) > -\frac{f(0)}{\mu_i} - \frac{1}{1-\gamma^2}\frac{b_i}{2\mu_i^2} - \frac{\gamma}{1-\gamma^2}\frac{b_j}{2\mu_i\mu_j}$ which is positive provided that $f(0) > -\frac{1}{1-\gamma^2}\frac{b_i}{2\mu_i} - \frac{\gamma}{1-\gamma^2}\frac{b_j}{2\mu_j} \equiv H_i(\gamma)$. Note that $H_i(\gamma)$ is strictly increasing in γ, with $H_i(0) = -\frac{b_i}{2\mu_i} < f(0)$ by Assumption 1, and $\lim_{\gamma\to 1} H_i(\gamma) = +\infty$. Let $\bar{\gamma}_i \in (0,1)$ denote the unique solution to $f(0) = H_i(\gamma)$ and $\Gamma = \min\{\bar{\gamma}_1, \bar{\gamma}_2\}$. Then, the equilibrium technologies are always positive for any $\gamma < \Gamma$.[22],[23] I make the following assumption which will hold for the rest of the analysis.

Assumption 2 (Upper Bound on Spillovers). $\gamma < \Gamma$.

Finally, note that a technological shock which increases the expected productivity of a division affects the upper bound Γ. However, as I will focus on positive technological shocks, it turns out that such shocks (weakly) increase the bound Γ thus relaxing the constraint on the size of cross-divisional spillovers.

[22]Note that Γ can be arbitrarily increased by increasing $f(0)$. For instance, for the parametrization $[a_1, b_1] = [a_2, b_2] = [1, 3]$, $\mu_1 = -2$, $\mu_2 = -1$ and $f(0) = 4.5$, it follows that $\Gamma = 0.7374$ which increases to $\Gamma = 0.8587$ if $f(0) = 8$.

[23]A similar approach has also been used by Calvó-Armengol, de Martí, and Prat (2012) to avoid corner solutions in a model that studies how pairwise communication affects the influence that agents have within organizations due to asymmetric payoff externalities.

3.2 Strategic communication and organizational performance

Given the intuition developed in the previous subsection, it should not be surprising that each division manager may try to misrepresent the riskiness of his division in order to distort the HQ manager's technological choice. This intuition is formalized in the next result where I also make use of the observation that $E_i[\nu_j] = \bar{\sigma}_j^2$, in equilibrium.

Lemma 1 (Incentive to Misreport Information). *If believed, each division manager would optimally misrepresent the riskiness of his division by inducing the posterior expectation*

$$\nu_i^* = \max\{\sigma_i^2 - B_i, a_i\} \tag{6}$$

where $B_i \equiv \gamma \left|\frac{\mu_i}{\mu_j}\right| \frac{\bar{\sigma}_j^2}{2} > 0$ *is division manager i's* bias.

The bias B_i *is increasing in the importance of spillovers,* γ*, the productivity gap,* $\left|\frac{\mu_i}{\mu_j}\right|$*, and the expected riskiness of division j,* $\bar{\sigma}_j^2$*.*

Each division manager would like to convince the HQ manager that the riskiness of his division is lower than it really is. This is because a division manager perceives that too little innovation is undertaken in his division due to the HQ manager's higher concern for spillovers. Likely, this incentive is not extreme. Suppose that the division manager reported a very low posterior expectation when the real one is high. As the HQ manager would choose a very large technology, the corresponding large increase in the riskiness of innovation would reduce the division's expected profitability. As I will show, this self-discipline effect will allow for informative communication to take place in equilibrium provided that the importance of spillovers is moderate.

Technological asymmetries affect a division manager's incentive to misreport through the productivity gap, $\left|\frac{\mu_i}{\mu_j}\right|$. An increase in the expected productivity of division j (i.e., $|\mu_j|$ increases) reduces the productivity gap as well as division manager i's incentive to lie. This is because such a technological shock leads the HQ manager to innovate more in division i which brings the level of innovation closer to the division manager's ideal level. A technological shock that increases the expected productivity of division i has instead multiple effects on division manager i's incentive to misreport. First, such a shock induces the HQ manager to adjust the level of innovation in division i which amplifies the division manager's perceived under-investment in innovation. Second, it leads to more innovation in division j (recall Proposition 1) which reduces expected spillovers and thus the expected profitability of division i, all else equal. Thus, the division manager responds to the shock by understating the riskiness of his division even further in order to counterbalance the HQ manager's lower incentive to innovate in his division.

Informational asymmetries affect the bias through a division manager's expectation about the riskiness of the other division. An increase in the expected riskiness of division j leads to a higher distortion in division manager i's report. As a higher $\bar{\sigma}_j^2$ makes lower innovation in division j more probable given the HQ manager's concern for spillovers, the resulting expected reduction in innovation in his own division induces more misreporting. Finally, an increase in the importance of spillovers also increases each division manager's bias due to the negative effect on the equilibrium level of innovation.

Lemma 1 highlights a simple but important insight: An increase in the productivity gap of innovation, $\left|\frac{\mu_i}{\mu_j}\right|$, affects the bias of both managers in opposite directions. This observation will have relevant consequences on the equilibrium level of informativeness of vertical communication. To this end, I need to introduce the following definition.

Definition 1. *Division i is (strategically)* weaker *than division j if* $\frac{(b_j)^2-(a_j)^2}{\mu_j^2} > \frac{(b_i)^2-(a_i)^2}{\mu_i^2}$.

Division i is weaker than division j if division i's manager has higher incentives to misreport compared to division j's manager. Suppose that $|\mu_i| = |\mu_j|$. If $|b_i - a_i| = |b_j - a_j|$, then division i is weaker when the expected riskiness of division j (i.e., $\bar{\sigma}_j^2$) is higher. This is because the bias of division i's manager is also higher. Similarly, suppose that $a_1 = a_2 = a$ and $b_1 = b_2 = b$, then division i being weaker than division j corresponds to $|\mu_i| > |\mu_j|$. Even though innovation in division i is more productive in expectation, division i's manager has once again higher incentives to understate the riskiness of his division by Lemma 1.

The concept of weakness is important in the characterization of equilibrium communication which is contained in Proposition 2 and illustrated in Figure 3.

Proposition 2 (Equilibrium Communication). *Suppose that division i is weaker than division j. There exist real numbers* $\gamma_i^* = \min\left\{\left|\frac{\mu_j}{\mu_i}\right| \frac{b_i-a_i}{b_j+a_j}, 1\right\}$, $i = 1, 2$, *with* $0 < \gamma_i^* < \gamma_j^*$ *such that:*[24]

(i) If $\gamma < \gamma_i^*$, then there exist integers $\bar{N}_i(B_i) > 1$ and $\bar{N}_j(B_j) > 1$ such that, for every positive integer $N_t \leq \bar{N}_t(B_t)$, $t = 1, 2$, there is at least one equilibrium in which:

(a) Division t's manager partitions her state space $[a_t, b_t]$ in the following way

$$n_{t,k+1} - n_{t,k} = n_{t,k} - n_{t,k-1} - 4B_t, \quad k = 1, ..., N_t - 1 \tag{7}$$

with $n_{t,0} = a_t$, $n_{t,N_t} = b_t$;

[24] As the upper bound on the importance of spillovers, Γ, is arbitrarily defined through $f(0)$, I assume that $\gamma_i^* < \Gamma$. However, $\gamma_j^* < \Gamma$ cannot the guaranteed because it might be the case that $\gamma_j^* = 1$.

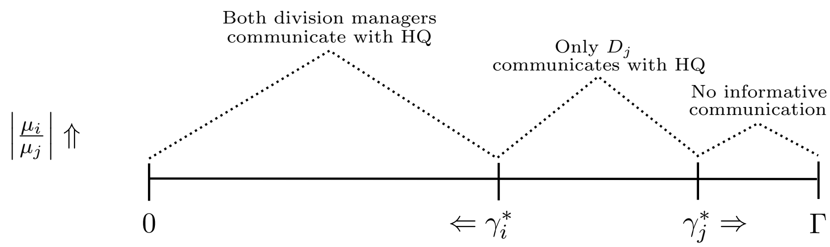

Figure 3: Structure of equilibrium communication.

(b) Division t's manager sends a message m_t *distributed uniformly over the support* $[n_{t,k-1}, n_{t,k}]$*, if* $\sigma_t^2 \in (n_{t,k-1}, n_{t,k})$*,* $k = 1, ..., N_t - 1$*;*

(c) The HQ manager holds a uniform posterior belief supported over $[n_{t,k-1}, n_{t,k}]$*, if* $m_t \in (n_{t,k-1}, n_{t,k})$*,* $k = 1, ..., N_t - 1$*;*

(d) The HQ manager's technology choices are given by (4).

(ii) If $\gamma \in \left[\gamma_i^*, \min\{\gamma_j^*, \Gamma\}\right)$*, then informative communication is only feasible between division j's manager and headquarters, whereas the only communication equilibrium with division i's manager involves babbling. The structure of equilibria is as in part* (*i*)*. In this case, the HQ manager innovates in division i only based on her prior information about the division's level of riskiness.*

(iii) If $\gamma \in \left[\min\{\gamma_j^*, \Gamma\}, \Gamma\right]$*, then vertical communication with both division managers is always uninformative and the HQ manager innovates in each division only based on prior information.*

Despite the complexities generated by technological uncertainty, the particular structure of each communication equilibrium is quite simple and it resembles the standard characterization familiar from Crawford and Sobel (1982). Whenever informative communication is feasible, each division manager partitions his state space and communicates only which element of the partition the realized riskiness of his division belongs to. Unlike in Crawford and Sobel, the size of the partitions is progressively smaller (rather than larger) because each division manager has an incentive to understate (rather than overstate) the riskiness of innovation in his division when communicating with headquarters.

However, the general structure of communication is more complex than in Crawford and Sobel because it depends both on the importance of spillovers for the organization as well as technological asymmetries across divisions. Technological asymmetries determine which division manager suffers a disadvantage. The manager of the least productive division, j, has higher incentives to communicate with headquarters because the HQ manager is less biased against innovation in that division, for any fixed level of spillovers γ.

The importance of spillovers determines who communicates with headquarters and whether informative communication is actually feasible. When spillovers are small, informative vertical communication is feasible between both division managers and headquarters.[25] As γ reaches an intermediate level, division manager i starts babbling whereas division manager j can still entertain informative communication with the HQ manager. Finally, if γ becomes sufficiently high, informative communication completely breaks down and the HQ manager chooses technologies only based on her prior information about the riskiness of each division.

The quality of vertical communication can be expressed in terms of the residual variance. Given that the bias is independent from the realized riskiness of each division, it is well-known from Crawford and Sobel that the residual variance of communication for an equilibrium with N_i partition elements can be expressed as

$$\Sigma_i^{N_i}(B_i) \equiv E\left[\left(\sigma_i^2 - \nu_i\right)^2\right] = E\left[(\sigma_i^2)^2\right] - E\left[\nu_i^2\right] = \frac{(b_i - a_i)^2}{12N_i^2} + B_i^2 \frac{N_i^2 - 1}{3} \tag{8}$$

which is minimized at $\bar{N}_i(B_i)$. As it is customary in the literature, I focus on the most informative communication equilibria from now on as those equilibria maximize ex-ante total expected profits.[26] I denote the corresponding residual variances simply as $\Sigma_i(B_i)$, $i = 1, 2$. Figure 4 maps the residual variance of vertical communication in the best communication equilibria as a function of the importance of technological spillovers.

As expected, an increase in the importance of spillovers reduces the quality of vertical communication because the HQ manager cares less about the expected profitability of each division. I instead focus attention on how technological shocks affect equilibrium communication.

Corollary 1 (Comparative statics: Technological Shocks). *Suppose that division i is weaker than division j. An increase in the productivity gap, $\left|\frac{\mu_i}{\mu_j}\right|$:*

1. *Decreases the quality of vertical communication with division manager i and increases the quality of communication with division manager j, for almost every γ;*

2. *Decreases the ability of division manager i to credibly communicate his private information (i.e., lower γ_i^*) and (weakly) increases the ability of division manager j.*

[25] As is well known, though, there always exists a babbling equilibrium in which no relevant information is transmitted.

[26] Those equilibria are also ex-ante preferred by each division manager.

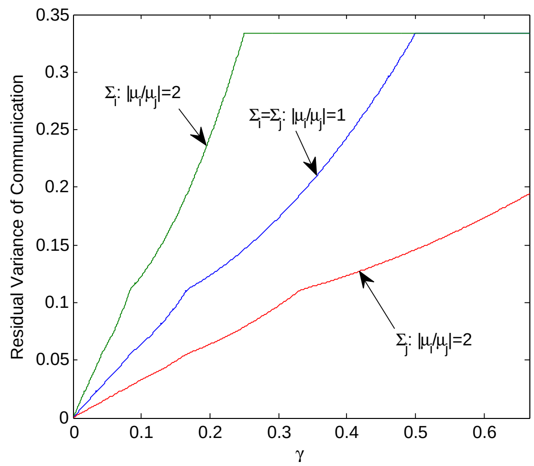

Figure 4: Residual variance for the best communication equilibria: $[a_i, b_i] = [a_j, b_j] = [1, 3]$, $\mu_i = -2$, $\mu_j = -1$.

Suppose that $\left|\frac{\mu_i}{\mu_j}\right| = 1$ *and that the importance of spillovers is small (i.e.,* $\gamma < \gamma_i^*$*), then an increase in the productivity gap decreases the aggregate informativeness of communication,* $\Sigma_i(B_i) + \Sigma_j(B_j)$*.*

Corollary 1 shows that a technological shock that affects the productivity gap, $\left|\frac{\mu_i}{\mu_j}\right|$, generates two effects on the quality of vertical communication. Suppose that division i is the weaker division. First, a shock that increases the expected productivity of innovation in division i (i.e., $|\mu_i| \uparrow$) decreases the quality of vertical communication between division i and headquarters whereas it increases communication between division j and headquarters. Given the HQ manager's concern for spillovers, a higher productivity of innovation makes it harder for division i's manager to be credible as he suffers higher incentives to understate his report to induce more innovation in his own division. Interestingly, even if no technological changes have occurred in the stronger division, division j's manager shares more information with headquarters after a shock that increases the expected productivity of division i. This effect stems from the fact that an increases in $|\mu_i|$ brings about more innovation in division j which makes innovation in that division closer to the ideal level perceived by its division manager. Thus, division j's manager has less incentives to misreport.

The second effect changes the feasibility of informative communication for each division manager. An increase in $|\mu_i|$ reduces the set of γ's for which informative communication is feasible between division i and headquarters. The reduction in the quality of vertical communication with division i implies that communication will necessarily break down if spillovers are sufficiently important for the organization. At the same time, a higher expected productivity of innovation in division i can make informative communication feasible for division j's manager for a larger set of γ's by making his report comparatively more credible.

An increase in the productivity gap also reduces the aggregate quality of vertical communication within the organization when spillovers are small. The increase in the informativeness of communication between division j's manager and headquarters is not enough to compensate for the lower incentives faced by division i's manager. This is the case even if the divisions were technologically similar before the shock, that is, $\left|\frac{\mu_i}{\mu_j}\right| = 1$.

Finally, I compute total expected profits.

PROPOSITION 3. *Total expected profits with centralized innovation are given by*

$$\Pi^C = E\left[\pi_1^C + \pi_2^C\right] = \sum_{k=1}^{2}\left\{\frac{f(0)}{\mu_k}\bar{\sigma}_k^2 + \frac{1}{1-\gamma^2}\frac{E\left[(\sigma_k^2)^2\right] - \Sigma_k(B_k)}{4\mu_k^2}\right\} + \frac{\gamma}{1-\gamma^2}\frac{\bar{\sigma}_i^2\bar{\sigma}_j^2}{2\mu_i\mu_j} \tag{9}$$

4 Organizational Change

So far, I have considered a centralized organization but in some instances authority over innovation can also be delegated to division managers. The literature has considered two different possibilities. Alonso, Dessein, and Matouschek (2008) and Rantakari (2008) have looked at the case in which decision rights can be credibly delegated. Baker, Gibbons, and Murphy (1999) have instead taken the different perspective that an organization can always take back decision rights so that delegation can only be achieved through relational contracts. In order to facilitate the comparison with centralized innovation, I follow the first approach and analyze innovation decisions under decentralized control. In particular, I assume that the HQ manager decides the allocation of authority before the division managers observe the riskiness of their divisions. I also allow for horizontal communication between division managers under delegated control.

I denote by $\nu_i = E_j[\sigma_i^2|m]$ the posterior expectation about σ_i^2 held by division manager j after receiving message m_i. Proposition 4 characterizes the equilibrium technologies under decentralized control.

PROPOSITION 4 (DECENTRALIZED INNOVATION). *Suppose Assumptions 1 and 2 hold. The equilibrium technologies with decentralized control are given by*

$$x_i^D(\sigma_i^2|\nu_i,\nu_j) = x_i^0(\sigma_i^2) - \frac{\gamma}{4-\gamma^2}\frac{\nu_j}{\mu_i\mu_j} - \frac{\gamma^2}{4-\gamma^2}\frac{\nu_i}{2\mu_i^2}, \quad i = 1,2,\ i \neq j. \tag{10}$$

Note that $\frac{\partial x_j^D}{\partial|\mu_i|} > 0$, *and* $\frac{\partial x_i^D}{\partial|\mu_i|} > 0$ *if, and only if,*

$$|\mu_i| < \frac{(4-\gamma^2)\sigma_i^2 + \gamma^2 \nu_i}{(4-\gamma^2)f(0) - \gamma \frac{\nu_j}{\mu_j}} \tag{11}$$

As one would expect, each division manager puts less weight on the posterior expectation about the riskiness of innovation in the other division than the HQ manager does because division managers care less about spillovers. Proposition 4 also shows that a technological shock that increases the productivity of innovation in a division leads the manager of the other division to be more innovative. However, the reaction of the manager of the division hit by the shock depends on the absolute size of the shock.

Unlike the case of centralization, no informative communication can take place in equilibrium between the division managers.[27] Given the form taken by spillovers in this model and the specification of uncertainty, each division has an extreme incentive to overstate the riskiness of his division. If division j's manager thinks that division i's riskiness is very high, he will innovate less in anticipation of lower innovation in division i as well due to the higher riskiness of innovation in that division. This is optimal because division j's manager can increase the expected profitability of his own division by trading off the risk associated with larger technologies for higher spillovers, which are less risky to pursue. This response, in turn, increases the expected outcome of innovation in division j which leads to higher expected technological spillovers for division i as well, for any given technology. Thus, *de facto*, divisions within the organization operate independently under decentralized control.

This observation leads to the following expression for total expected profits

$$\Pi^D = E\left[\pi_1^D + \pi_2^D\right] = \sum_{k=1}^{2} \left\{ \frac{f(0)}{\mu_k}\bar{\sigma}_k^2 + \frac{E\left[\left(\sigma_k^2\right)^2\right]}{4\mu_k^2} + \frac{\gamma^2(12-\gamma^2)}{(4-\gamma^2)^2}\frac{\left(\bar{\sigma}_k^2\right)^2}{4\mu_k^2} \right\} + \frac{8\gamma}{(4-\gamma^2)^2}\frac{\bar{\sigma}_i^2\bar{\sigma}_j^2}{\mu_i\mu_j} \tag{12}$$

It can also be shown that decentralized innovation outperforms centralized innovation when the importance of spillovers vanishes, even without informative horizontal communication between division managers.[28]

[27] The proof is omitted but the details are available from the author upon request.

[28] I show this result in footnote 41, as part of the proof of Theorem 1. This result was first formalized by Dessein (2002) and later extended by Alonso, Dessein, and Matouschek (2008) and Rantakari (2008) to organizations facing a trade-off between coordination and adaptation. This "delegation principle" thus continues to hold in environments in which technological spillovers are present and technologies are risky. More recently, Alonso, Dessein, and Matouschek (2012) have however shown that the delegation principle

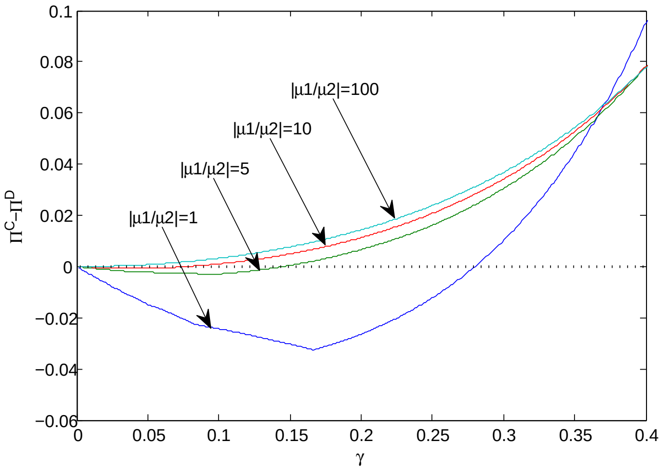

Figure 5: Effect of a technological shock to the expected productivity of division 1 for small values of γ: $[a_1, b_1] = [a_2, b_2] = [1, 3]$, $f(0) = 9$, and $|\mu_2| = 1$.

I instead focus attention on how technological shocks to a division's productivity affect the performance differential between the two allocations of authority. Figure 5 illustrates this link when the importance of spillovers, γ, is small.

THEOREM 1 (ORGANIZATIONAL CHANGE WITH SMALL SPILLOVERS). *Suppose that* $[a_i, b_i] = [a_j, b_j]$ *and* $\left|\frac{\mu_i}{\mu_j}\right| \geq 1$, *that is, division* i *is possibly weaker than division* j.[29] *When spillovers are small (i.e.,* γ *is small), a technological shock that increases the productivity of division* i, *that is,* $|\mu_i|$, *increases the attractiveness of centralized over decentralized innovation.*

Theorem 1 shows that a technological shock that increases the productivity gap between divisions may affect the allocation of authority over innovation, that is, it might induce organizational change. When the importance of spillovers is not too large, a sufficiently large technological shock which further increases the productivity gap may induce the organization to centralize authority when authority was initially delegated. Centralization becomes more appealing for two reasons: *i*) it helps the organization to curb the innovative ambitions of the manager of the most productive division; and *ii*) centralization improves internal communication compared to decentralization. To understand why, we need to consider the effects induced by an increase in the expected productivity of division i, which is the more

might fail even when incentives are sufficiently aligned within the organization, provided that production decisions in each division are strategic complements and sufficiently interdependent.

[29] The assumption that $[a_i, b_i] = [a_j, b_j]$ is just to simplify the calculations. The theorem remains true even if $[a_i, b_i] \neq [a_j, b_j]$ and division i is weaker than division j.

productive division. Recall from Proposition 1 that an increase in $|\mu_i|$ might either increase or decrease division manager i's incentive to innovate depending on the way in which the shock affects that manager's risk-return trade-off. However, regardless of the direction of innovation after the shock, the HQ manager would be more responsive than the manager is to a technological shock because she fully internalizes the importance of externalities for the organization. This effect favors centralization over decentralization and it gets stronger as the size of the shock increases. A second effect arises from the observation that a technological shock also increases the sensitivity of spillovers to innovation performed within the division affected by the shock, even if the absolute importance of spillovers (i.e., γ) is unchanged. This is because the shock favors division-specific innovation which is thus less likely to generate positive spillovers for the other division. This makes communication relatively more important for organizational performance and communication is better under centralization than decentralization, even if a positive technological shock may actually reduce the aggregate informativeness of vertical communication.[30]

When the importance of spillovers is large, the equilibrium technologies are more sensitive to technological shocks, that is, $\frac{\partial^2 x_i^C}{\partial|\mu_i|\partial\gamma} > 0$. This is because larger spillovers amplify the effect that innovation has on organizational performance. Furthermore, large spillovers are already associated with a low quality of vertical communication because division managers have higher incentives to misreport. As a positive technological shock will decrease the quality of communication even further precisely when information is most need, decentralization may become more attractive because it guarantees an optimal use of information. This intuition is formalized in the next result.

PROPOSITION 5 (Large Spillovers). *Suppose that* $[a_i, b_i] = [a_j, b_j]$ *and* $\left|\frac{\mu_i}{\mu_j}\right| = 1$. *If*

$$\frac{\gamma}{1-\gamma} - \frac{16\gamma + 12\gamma^2 - \gamma^4}{(4-\gamma^2)^2} > \frac{1}{3}\left(\frac{b-a}{b+a}\right)^2 \tag{13}$$

a technological shock that increases the productivity of division i, that is, $|\mu_i|$, *increases the attractiveness of decentralized over centralized innovation.*

However, as Figure 6 shows, even a large technological shock may not be able to induce the organization to decentralize authority when spillovers are sufficiently important. This is because the sheer importance of spillovers for organizational performance, and thus the

[30] Recall from Corollary 1 that an increase in $|\mu_i|$ lowers the quality of communication between manager i and headquarters whereas it increases communication with division j. However, the overall quality of vertical communication may go down after such a shock.

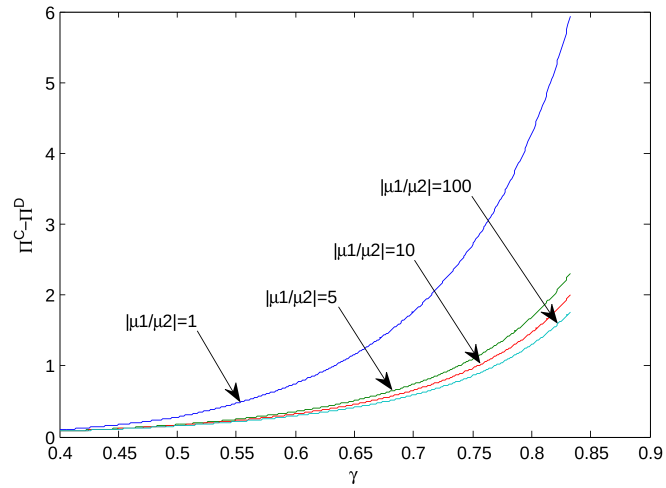

Figure 6: Effect of a technological shock to the expected productivity of division 1 for large values of γ: $[a_1, b_1] = [a_2, b_2] = [1, 3]$, $f(0) = 9$, and $|\mu_2| = 1$.

need to coordinate innovation across divisions, may dominate any other effect.

Going back to IBM: When the PC division was set up, IBM delegated most of the decision-making authority to the managers of that division which provided significant autonomy. A reason justifying that decision can be found in the fact that the importance of spillovers between innovation decisions in the two divisions was small. However, there are signs that strategic communication might have also been an issue. As Bresnahan, Greenstein, and Henderson (2007, footnote 27) note, the managers of the PC division "believed that the market potential [of the personal computer] was large, but dared not say so in their first presentations to the CMC [Corporate Management Committee] in deference to the prevailing sensibilities. The division's official forecast for sales was deliberately chosen to not exceed the total number of IBM worldwide installations at the time, just over two hundred thousand. In fact, sales of the first models eventually exceeded several million units" and "the original proposal for the design of the PC explicitly did not propose a leading-edge design at the frontier of microprocessors for fear that doing so would get the entire project politically derailed over cannibalizing IBM's (already sputtering) minicomputer product line."(BGH 2007, pag. 31). IBM had already faced failure in a previous attempt to develop the IBM 4300, which was targeting the minicomputer market. IBM's executives "concluded that the decision-making process itself had led the firm to develop an ineffective product." (BGH 2007, pag. 19). In particular, the decision-making process favored the interests of the mainframe division (i.e., spillovers) against market needs.

With large authority over decisions, the managers of the PC division experimented with many new designs and technical choices that presented several risks. For example, they decided to embrace an open systems approach by using parts from other suppliers rather than developing proprietary technology, which was IBM's approach in the mainframe division.

The large success of the personal computer took many by surprise. This success changed expectations about the PC division which, in the context of this model, may be thought of as a technological shock that increased the expected productivity of the PC division.[31] This shock, paradoxically, worsened the PC division's position within the organization. As a result, the division was centralized and IBM imposed a return to the traditional approach that focused on proprietary products. Centralization, however, helped to realign the PC division with the rest of the organization as "the PC division did, in fact, aspire to act like other divisions of IBM–in the sense that it aimed to release new PC products–only after internal consultation and deliberation–that were technically reliable, priced with high margins, and introduced later than competitors." (BGH 2007, pag. 37) Thus, centralization curbed the innovative ambitions of the "wild ducks" and fostered more communication within the organization whereas the PC division initially acted "like an entrant."[32]

5 Conclusion

This paper provides a framework to study the management of innovation in organizations that share cross-divisional, technological spillovers. I investigate how the trade-off between centralization and decentralization is affected by technological asymmetries across divisions and the riskiness of innovation as the choice of a technology affects both the expectation and the variance of firm's profits. I identify a mechanism through which a technological shock to the expected productivity of a division might propagate within an organization and determine organizational change. As technological asymmetries affect the incentives to communicate information in asymmetric ways, I show that the effect of a shock on organizational change depends on the absolute importance of spillovers for the organization. When the importance

[31] However, the riskiness of innovation was still high.

[32] The reader may have noticed that IBM delegated authority to the PC division but it kept the mainframe division centralized. Even though I analyzed only the case of complete decentralization in both divisions, the analysis can be extended to the case in which division i is decentralized whereas division j is centralized. I can also allow division i to communicate with headquarters and division j to communicate both with headquarters and division i. Even in this case the division manager of the decentralized division would act independently and without communicating any relevant information to headquarters due to his extreme incentive to distort his report.

of spillovers is moderate, a positive shock to a single division's expected productivity may lead the organization to centralize authority, when authority was initially decentralized. If the importance of spillovers is higher, a similar shock may instead increase the attractiveness of decentralization. These results derive from the effect that a technological shock has on the inherent trade-off between the productivity of innovation, the risks of innovation, and the sensitivity of cross-divisional spillovers to innovation.

The paper could be extended in several dimensions. The first obvious extension is to multiple stages of sequential innovation rather than just one. A dynamic extension would induce two additional issues. First, the observation of the outcomes of innovation would lead all the agents in the organization to learn more about the technological landscape. This is possible because knowledge of additional coordinates of the path of a Brownian motion carries information about other, untried technologies.[33] Second, the outcome of past innovation may also play an important role in the headquarters' decision to change the internal allocation of authority over time due to a time-varying, endogenous need for coordination in the presence of spillovers.[34] These extensions present interesting modeling challenges which I hope to investigate in future research.

A Omitted Proofs

Proof of Proposition 1: The HQ manager chooses $(x_1, x_2) \in \mathbb{R}^2_+$ to maximize total expected profits which are given by

$$\begin{aligned} E[\pi_1^\gamma + \pi_2^\gamma | m, x_1, x_2] &= -\sum_{i=1,2} E[f_i(x_i)^2 | m, x_i] + 2\gamma E\left[f_1(x_1) f_2(x_2) | m, x_1, x_2\right] \\ &= -\sum_{i=1,2} E\left[E[f_i(x_i)^2 | m, x_i, \sigma_i^2] | m, x_i\right] + 2\gamma E\left[E[f_1(x_1)|x_1, m] E[f_2(x_2)|x_2, m] | m\right] \\ &= -\sum_{i=1,2} E[(f(0) + \mu_i x_i)^2 + \sigma_i^2 x_i | m, x_i] + 2\gamma (f(0) + \mu_1 x_1)(f(0) + \mu_2 x_2) \\ &= -\sum_{i=1,2} \left[(f(0) + \mu_i x_i)^2 + \nu_i x_i\right] + 2\gamma (f(0) + \mu_1 x_1)(f(0) + \mu_2 x_2) \quad (14) \end{aligned}$$

where the second equality follows from the normality of the outcome functions and the independence between the Brownian motions generating outcomes in each division. The

[33] I tried to pursue this extension directly but the analysis proved to be quite complex. Thus, additional research would be needed.

[34] In another paper, I started to investigate the link between past innovation successes and the incentives to reallocate authority in a different type of model (see, Garfagnini 2013).

first-order conditions of this constrained maximization problem are given by

$$\frac{\partial \mathcal{L}}{\partial x_i} = -2\mu_i(f(0)+\mu_i x_i) - \nu_i + 2\gamma\mu_i(f(0)+\mu_j x_j) \leq 0, \quad i=1,2,\ i\neq j \tag{15}$$

$$x_i \frac{\partial \mathcal{L}}{\partial x_i} = 0, \quad i=1,2 \tag{16}$$

Lemma 2 provides a complete characterization of the HQ manager's maximization problem. Before I state the lemma, it is convenient to introduce the following notation,

$$G_\gamma(w,z) = \frac{1}{1-\gamma^2}w + \frac{\gamma}{1-\gamma^2}z. \tag{17}$$

Lemma 2. *Suppose that* $\frac{\nu_i}{\mu_i} \geq \frac{\nu_j}{\mu_j}$*. Then, the HQ manager chooses the technologies*

$$x_i^C(\nu_i,\nu_j) = \begin{cases} -\frac{f(0)}{\mu_i} - \frac{1}{1-\gamma^2}\frac{\nu_i}{2\mu_i^2} - \frac{\gamma}{1-\gamma^2}\frac{\nu_j}{2\mu_i\mu_j} & \textit{if } f(0) > -G_\gamma\left(\frac{\nu_j}{2\mu_j},\frac{\nu_i}{2\mu_i}\right) \\ -(1-\gamma)\frac{f(0)}{\mu_i} - \frac{\nu_i}{2\mu_i^2} & \textit{if } -\frac{1}{1-\gamma}\frac{\nu_i}{2\mu_i} \leq f(0) \leq \\ & \quad \leq -G_\gamma\left(\frac{\nu_j}{2\mu_j},\frac{\nu_i}{2\mu_i}\right) \\ 0 & \textit{if } f(0) < -\frac{1}{1-\gamma}\frac{\nu_i}{2\mu_i} \end{cases} \tag{18}$$

$$x_j^C(\nu_j,\nu_i) = \begin{cases} -\frac{f(0)}{\mu_i} - \frac{1}{1-\gamma^2}\frac{\nu_j}{2\mu_j^2} - \frac{\gamma}{1-\gamma^2}\frac{\nu_i}{2\mu_i\mu_j} & \textit{if } f(0) > -G_\gamma\left(\frac{\nu_j}{2\mu_j},\frac{\nu_i}{2\mu_i}\right) \\ 0 & \textit{otherwise.} \end{cases} \tag{19}$$

Proof. Suppose first that $x_i > 0$ and $x_j > 0$. Then, (15) and (16) give

$$x_i = -\frac{f(0)}{\mu_i} - \frac{\nu_i}{2\mu_i^2} + \frac{\gamma}{\mu_i}(f(0)+\mu_j x_j), \quad i=1,2,\ i\neq j \tag{20}$$

Solving the system of equations (20) and rearranging gives

$$x_i = -\frac{f(0)}{\mu_i} - \frac{1}{1-\gamma^2}\frac{\nu_i}{2\mu_i^2} - \frac{\gamma}{1-\gamma^2}\frac{\nu_j}{2\mu_i\mu_j} \tag{21}$$

which is positive if, and only if, $f(0) > -G_\gamma\left(\frac{\nu_i}{2\mu_i},\frac{\nu_j}{2\mu_j}\right)$. A similar calculation holds for technology x_j. Note that $\frac{\nu_i}{\mu_i} \geq \frac{\nu_j}{\mu_j}$ implies that $-G_\gamma\left(\frac{\nu_i}{2\mu_i},\frac{\nu_j}{2\mu_j}\right) \leq -G_\gamma\left(\frac{\nu_j}{2\mu_j},\frac{\nu_i}{2\mu_i}\right)$. Thus, both technologies are indeed positive if, and only if, $f(0) > -G_\gamma\left(\frac{\nu_j}{2\mu_j},\frac{\nu_i}{2\mu_i}\right)$. As this is an interior solution, I still need to check the second-order conditions to verify whether the point is a maximum or not. Note that

$$\frac{\partial^2 E[\pi_1^\gamma + \pi_2^\gamma | m]}{\partial x_i^2} = -2\mu_i^2 < 0, \quad \text{and} \quad \frac{\partial^2 E[\pi_1^\gamma + \pi_2^\gamma | m]}{\partial x_i \partial x_j} = 2\gamma\mu_i\mu_j \tag{22}$$

Thus,

$$\frac{\partial^2 E[\pi_1^\gamma + \pi_2^\gamma | m]}{\partial x_1^2}\frac{\partial^2 E[\pi_1^\gamma + \pi_2^\gamma | m]}{\partial x_2^2} - \left[\frac{\partial^2 E[\pi_1^\gamma + \pi_2^\gamma | m]}{\partial x_1 \partial x_2}\right]^2 = 4\mu_i^2\mu_j^2(1-\gamma^2) > 0, \quad \forall\, \gamma < 1 \tag{23}$$

Since the Hessian is negative definite, the objective function is strictly concave thus proving that the stationary point is a global maximum.

Next, consider the case $f(0) \leq -G_\gamma\left(\frac{\nu_j}{2\mu_j}, \frac{\nu_i}{2\mu_i}\right)$. Suppose that $x_j = 0$ and $x_i > 0$. The first-order conditions with respect to x_j give

$$\left.\frac{\partial \mathcal{L}}{\partial x_j}\right|_{x_j=0} \leq 0 \iff f(0) + \mu_i x_i \geq \frac{f(0)}{\gamma} + \frac{\nu_j}{2\gamma\mu_j} \tag{24}$$

Furthermore, from the first-order conditions for x_i, which must hold with equality, I have that

$$x_i = -\frac{1-\gamma}{\mu_i} f(0) - \frac{\nu_i}{2\mu_i^2} \tag{25}$$

Substituting (25) into (24), I obtain that $\left.\frac{\partial \mathcal{L}}{\partial x_j}\right|_{x_j=0} \leq 0$ if, and only if, $f(0) \leq -G_\gamma\left(\frac{\nu_j}{2\mu_j}, \frac{\nu_i}{2\mu_i}\right)$, which is the condition I started from. In order to guarantee that $x_i > 0$, it must be the case that $f(0) > -\frac{1}{1-\gamma}\frac{\nu_i}{2\mu_i}$. As $\frac{\nu_i}{\mu_i} \geq \frac{\nu_j}{\mu_j}$ by assumption, it also follows that $-\frac{1}{1-\gamma}\frac{\nu_i}{2\mu_i} \leq -G_\gamma\left(\frac{\nu_i}{2\mu_i}, \frac{\nu_j}{2\mu_j}\right) \leq -G_\gamma\left(\frac{\nu_j}{2\mu_j}, \frac{\nu_i}{2\mu_i}\right)$. A similar analysis to the previous case shows that in order to have $x_i = 0$ and $x_j > 0$ as a solution of the first-order conditions, it must also be the case that $f(0) \leq -G_\gamma\left(\frac{\nu_i}{2\mu_i}, \frac{\nu_j}{2\mu_j}\right)$ and $f(0) > -\frac{1}{1-\gamma}\frac{\nu_j}{2\mu_j}$. However, $\frac{\nu_i}{\mu_i} \geq \frac{\nu_j}{\mu_j}$ implies that $-\frac{1}{1-\gamma}\frac{\nu_j}{2\mu_j} \geq -G_\gamma\left(\frac{\nu_i}{2\mu_i}, \frac{\nu_j}{2\mu_j}\right)$. Thus, this case cannot arise. This is intuitive because if, for instance, $\mu_i = \mu_j$, the reported riskiness is higher in division j than in division i and, given that there is no innovation in division i, there should not be any innovation in division j either because innovation would be even riskier. To sum up, if $-\frac{1}{1-\gamma}\frac{\nu_i}{2\mu_i} < f(0) \leq -G_\gamma\left(\frac{\nu_j}{2\mu_i}, \frac{\nu_i}{2\mu_i}\right)$, the unique solution to the first-order conditions is given by $x_j = 0$ and $x_i > 0$.

The last case to consider is $x_i = x_j = 0$ which exactly requires that $f(0) \leq -\frac{1}{1-\gamma}\frac{\nu_i}{2\mu_i}$. As the only constraints involved are non-negativity constraints, an analysis of the bordered Hessian matrix (with the appropriate binding non-negativity constraints) shows that the stationary points I identified are indeed global maxima. □

Most of the comparative statics results stated in the proposition follow immediately from (4). Next, suppose that $f(0) > -G_\gamma\left(\frac{\nu_j}{2\mu_j}, \frac{\nu_i}{2\mu_i}\right)$, then

$$\frac{\partial x_i^C}{\partial|\mu_i|} = -\frac{1}{\mu_i^2}\left[f(0) - \frac{1}{1-\gamma^2}\frac{\nu_i}{|\mu_i|} - \frac{\gamma}{1-\gamma^2}\frac{\nu_j}{2|\mu_j|}\right] \tag{26}$$

which is positive if, and only if, $|\mu_i| < \frac{\nu_i}{(1-\gamma^2)f(0)-\gamma\frac{\nu_j}{2|\mu_j|}}$ which is well-defined provided that $f(0) > \frac{\gamma}{1-\gamma^2}\frac{\nu_j}{2|\mu_j|}$. This is the case because $f(0) > -G_\gamma\left(\frac{\nu_j}{2\mu_j}, \frac{\nu_i}{2\mu_i}\right)$.

Finally, given that there is a one-to-one mapping between $f(0)$ and γ, the conditions of Lemma 2 can equivalently be stated in terms of γ rather than $f(0)$.

Proof of Lemma 1: Fix any arbitrary communication rule, $\beta_j(\cdot)$, for division j's manager. Given that $\gamma < \Gamma$, using (4) I can write the expected profits of division i conditional on σ_i^2 and ν_i as

$$\begin{aligned} E_i\left[\pi_i^\gamma\left(x_i^C, x_j^C\right)\middle|\, \sigma_i^2, \nu_i, \beta_j(\cdot)\right] =& \sigma_i^2\frac{f(0)}{\mu_i} + \frac{1}{1-\gamma^2}\frac{\sigma_i^2\nu_i}{2\mu_i^2} - \frac{1}{1-\gamma^2}\frac{\nu_i^2}{4\mu_i^2} \\ &+ \frac{\gamma}{1-\gamma^2}\frac{\sigma_i^2 E_i[\nu_j|\beta_j(\cdot)]}{2\mu_i\mu_j} - \frac{\gamma}{1-\gamma^2}\frac{\nu_i E_i[\nu_j|\beta_j(\cdot)]}{4\mu_i\mu_j} \end{aligned} \tag{27}$$

Differentiating with respect to ν_i gives

$$\frac{\partial E_i\left[\pi_i^\gamma\left(x_i^C, x_j^C\right)\middle|\, \sigma_i^2, \nu_i, \beta_j(\cdot)\right]}{\partial\nu_i} = \frac{1}{1-\gamma^2}\frac{\sigma_i^2}{2\mu_i^2} - \frac{1}{1-\gamma^2}\frac{\nu_i}{2\mu_i^2} - \frac{\gamma}{1-\gamma^2}\frac{E_i[\nu_j|\beta_j(\cdot)]}{4\mu_i\mu_j} \tag{28}$$

As $\frac{\partial^2 E_i\left[\pi_i^\gamma\left(x_i^C, x_j^C\right)\middle|\sigma_i^2, \nu_i, \beta_j(\cdot)\right]}{\partial(\nu_i)^2} = -\frac{1}{2\mu_i^2(1-\gamma^2)} < 0$, (28) implies that $\nu_i^* = \sigma_i^2 - \gamma\left|\frac{\mu_i}{\mu_j}\right|\frac{E_i[\nu_j|\beta_j(\cdot)]}{2}$ if the solution is interior and $\nu_i^* = a_i$ if $\sigma_i^2 \leq a_i + \gamma\left|\frac{\mu_i}{\mu_j}\right|\frac{E_i[\nu_j|\beta_j(\cdot)]}{2}$. Finally, as I shall prove in Proposition 2, $E_i[\nu_j|\beta_j(\cdot)] = \bar{\sigma}_j^2$ in equilibrium. A similar derivation can be obtained for division j's manager. This completes the proof.

Proof of Proposition 2: I first show that all communication rules for division i's manager in equilibrium are partition equilibria, and similarly for division j's manager. Fix an arbitrary communication rule, $\beta_j(\cdot)$, for division j's manager. Differentiating (28) with respect to σ_i^2 gives

$$\frac{\partial^2 E_i\left[\pi_i^\gamma\left(x_i^C, x_j^C\right)|\sigma_i^2, \nu_i, \beta_j(\cdot)\right]}{\partial(\sigma_i^2)\partial\nu_i} = \frac{1}{1-\gamma^2}\frac{1}{2\mu_i^2} > 0 \tag{29}$$

Supermodularity in (σ_i^2, ν_i) implies that there can only be one type of division i that is indifferent between two posterior expectations. Suppose also, by way of contradiction, that there exist two types of division i, $\hat{\sigma}_i^2 > \tilde{\sigma}_i^2$, and two posterior expectations, $\hat{\nu}_i > \tilde{\nu}_i$, such that

$$E_i\left[\pi_i^\gamma\left(x_i^C, x_j^C\right)\middle|\, \hat{\sigma}_i^2, \tilde{\nu}_i, \beta_j(\cdot)\right] > E_i\left[\pi_i^\gamma\left(x_i^C, x_j^C\right)\middle|\, \hat{\sigma}_i^2, \hat{\nu}_i, \beta_j(\cdot)\right] \tag{30}$$

$$E_i\left[\pi_i^\gamma\left(x_i^C, x_j^C\right)\middle|\, \tilde{\sigma}_i^2, \hat{\nu}_i, \beta_j(\cdot)\right] \geq E_i\left[\pi_i^\gamma\left(x_i^C, x_j^C\right)\middle|\, \tilde{\sigma}_i^2, \tilde{\nu}_i, \beta_j(\cdot)\right] \tag{31}$$

That is, the high type prefers to induce the lower posterior expectation whereas the low type has the opposite preference. Rearranging both inequalities gives that the expected utility of the low type increases more than that of the high type by increasing the posterior expectation from $\tilde{\nu}_i$ to $\hat{\nu}_i$, which contradicts (29). This implies that a higher type prefers to induce a weakly higher posterior expectation which establishes the claim.

Next, fix a partition $\{n_{i,0} = a_i, ..., n_{i,k}, ...n_{i,N_i} = b_i\}$ of $[a_i, b_i]$. If division i's manager sends a message $m_i \in (n_{i,k-1}, n_{i,k})$, I denote the posterior expectation held by the HQ manager upon receiving that message by $\nu_{i,k}$. Then, it must be the case that the boundary type $n_{i,k}$ is indifferent between inducing the posterior expectations $\nu_{i,k}$ and $\nu_{i,k+1}$, that is,

$$\begin{aligned} 0 &= E_i\left[\pi_i^C\middle|\, n_{i,k}, \nu_{i,k}, \beta_j(\cdot)\right] - E_i\left[\pi_i^C\middle|\, n_{i,k}, \nu_{i,k+1}, \beta_j(\cdot)\right] = \\ &= -\frac{\nu_{i,k} - \nu_{i,k+1}}{2\mu_i^2(1-\gamma^2)}\left\{-n_{i,k} + \gamma\frac{\mu_i}{\mu_j}\frac{E_i[\nu_j|\beta_j(\cdot)]}{2} + \frac{\nu_{i,k} + \nu_{i,k+1}}{2}\right\}\end{aligned}$$

This is zero if, and only if, either $\nu_{i,k} = \nu_{i,k+1}$ or else the term in curly brackets is zero. Rearranging the latter, substituting for $\nu_{i,k} = \frac{n_{i,k}+n_{i,k-1}}{2}$, and using once again the equilibrium condition $E_i[\nu_j|\beta_j(\cdot)] = \bar{\sigma}_j^2$, I obtain the following recursive equation

$$n_{i,k+1} - n_{i,k} = n_{i,k} - n_{i,k-1} - 4B_i \tag{32}$$

where $B_i = \gamma\left|\frac{\mu_i}{\mu_j}\right|\frac{\bar{\sigma}_j^2}{2}$. Equation (32) is similar to the recursive equation arising in the main example in Crawford and Sobel (1982) with the constant bias B_i. Thus, as in Crawford and Sobel (1982), the largest number of intervals achievable in a partition equilibrium, $\bar{N}_i(B_i)$, is the largest positive integer such that $2N(N-1)B_i < b_i - a_i$ which is given by,[35]

$$\bar{N}_i(B_i) = \left\lfloor \frac{1}{2} + \frac{1}{2}\left(1 + \frac{2(b_i - a_i)}{B_i}\right)^{1/2}\right\rfloor \tag{33}$$

[35] $\lfloor x \rfloor$ denotes the largest integer smaller than or equal to x.

A necessary condition for the existence of a nontrivial partition equilibrium is that $B_i < \frac{b_i - a_i}{4}$ or, equivalently, $\gamma < \left|\frac{\mu_j}{\mu_i}\right| \frac{b_i - a_i}{b_j + a_j} \equiv A_i$, where I used the fact that $\bar{\sigma}_j^2 = \frac{b_j + a_j}{2}$ from the uniform prior. Define $\gamma_i^* = \min\{A_i, 1\}$. Suppose that $A_j \geq 1$, this leads to the chain of inequalities

$$1 \geq \left|\frac{\mu_j}{\mu_i}\right| \frac{b_i + a_i}{b_j - a_j} > \left|\frac{\mu_j}{\mu_i}\right| \frac{b_i - a_i}{b_j + a_j} = A_i \tag{34}$$

Thus, $A_j \geq 1$ implies that $A_i < 1$. Furthermore, $A_j > A_i$ is equivalent to $\frac{b_j^2 - a_j^2}{\mu_j^2} > \frac{b_i^2 - a_i^2}{\mu_i^2}$, that is, division i is weaker than division j. Assuming that division i is weaker than division j implies that $\gamma_i^* < \gamma_j^*$ but it could be the case that $\gamma_j^* > \Gamma$.[36] Thus: *i*) if $\gamma < \gamma_i^*$, there exist communication equilibria between both division managers and the HQ manager for any $1 \leq N_i \leq \bar{N}_i(B_i)$ and $1 \leq N_j \leq \bar{N}_j(B_j)$, respectively; *ii*) if $\gamma \in [\gamma_i^*, \min\{\gamma_j^*, \Gamma\})$, the only communication equilibrium between division i's manager and the HQ manager is the babbling equilibrium whereas there exists a communication equilibrium between division j's manager and the HQ manager for any $1 \leq N_j \leq \bar{N}_j(B_j)$; and *iii*) if $\gamma \geq \min\{\gamma_j^*, \Gamma\}$, then the only communication equilibria involve babbling. Finally, note that all communication equilibria satisfy the condition that $E_k[\nu_i] = \bar{\sigma}_i^2$, $i = 1, 2$ and $k \in \{1, 2, HQ\}$.

Proof of Corollary 1: 1.) Note that $\Sigma_i(B_i)$ is a continuous and differentiable function of $\left|\frac{\mu_i}{\mu_j}\right|$, all else equal, over the interval $(0, +\infty)$ except at a countable number of points which correspond to the points of discontinuity of $\bar{N}_i(B_i)$. Let D_i denote the set of such discontinuity points. Take any $z \in (0, +\infty) \setminus D_i$, then

$$\left.\frac{d\Sigma_i(B_i)}{d\left|\frac{\mu_i}{\mu_j}\right|}\right|_{\left|\frac{\mu_i}{\mu_j}\right| = z} = \frac{\gamma^2}{2}(\bar{\sigma}_j^2)^2 z \frac{\bar{N}_i(B_i)^2 - 1}{3} > 0 \tag{35}$$

Thus, $\Sigma_i(B_i)$ is increasing in $\left|\frac{\mu_i}{\mu_j}\right|$ at all points of $(0, +\infty) \setminus D_i$ and D_i is a set of measure zero because it is countable. Similarly,

$$\left.\frac{d\Sigma_j(B_j)}{d\left|\frac{\mu_i}{\mu_j}\right|}\right|_{\left|\frac{\mu_i}{\mu_j}\right| = z} = -\frac{\gamma^2}{2}(\bar{\sigma}_i^2)^2 \frac{1}{z^3} \frac{\bar{N}_j(B_j)^2 - 1}{3} < 0, \quad \forall\, z \in (0, +\infty) \setminus D_j \tag{36}$$

2.) It follows from direct differentiation of the expressions for γ_i^* and γ_j^*. Given that I

[36] Given that Γ can be chosen arbitrarily close to (but strictly less than) 1, I assume without loss of generality that $\gamma_i^* < \Gamma$.

assumed $\gamma_j^* > \gamma_i^*$, an increase in $\left|\frac{\mu_i}{\mu_j}\right|$ increases γ_j^* only provided that $\gamma_j^* < \Gamma$.

Finally, suppose that $\gamma < \gamma_i^*$ so that informative communication is feasible with both division managers in equilibrium. Let $z \in (0, +\infty)\backslash D$, where $D = D_i \cup D_j$, then $\left.\frac{d(\Sigma_i(B_i)+\Sigma_j(B_j))}{dz}\right|_{z=1} =$ 0 but

$$\left.\frac{d^2(\Sigma_i(B_i) + \Sigma_j(B_j))}{dz^2}\right|_{z=1} = \frac{\gamma^2}{2}(\bar{\sigma}_j^2)^2\frac{\bar{N}_i(B_i)^2 - 1}{3} + \frac{\gamma^2}{2}(\bar{\sigma}_i^2)^2\left(\bar{N}_j(B_j)^2 - 1\right) > 0. \tag{37}$$

This completes the proof.

Proof of Proposition 3: From Proposition 2 and lengthy calculations, total expected profits for a given pair of communication equilibria with N_i and N_j partition elements, respectively, are given by

$$\Pi^C = E\left[\pi_1^C + \pi_2^C\right] = \sum_{k=1}^{2}\left\{\frac{f(0)}{\mu_k}\bar{\sigma}_k^2 + \frac{1}{1-\gamma^2}\frac{E\left[(\sigma_k^2)^2\right] - \Sigma_k^{N_k}(B_i)}{4\mu_k^2}\right\} + \frac{\gamma}{1-\gamma^2}\frac{\bar{\sigma}_i^2\bar{\sigma}_j^2}{2\mu_i\mu_j} \tag{38}$$

where I used the fact that $E[\sigma_i^2\nu_i] = E\left[E\left[\sigma_i^2\nu_i|\sigma_i^2 \in (n_{i,k-1}, n_{i,k})\right]\right] = E\left[\nu_i^2\right]$. $\Sigma_i^{N_i}(B_i) = E\left[(\sigma_i^2)^2\right] - E\left[\nu_i^2\right]$ denotes the residual variance of communication between division i's manager and the HQ manager.[37] Note that total expected profits are maximized by the communication equilibria with the largest number of partition elements because those equilibria are also associated with the lowest residual variances.

Proof of Proposition 4: Division i's manager maximizes the expected profits of his division given his private information and the information that has been exchanged with the other division manager. Division i's expected profits can be written as follows

$$E_i[\pi_i^\gamma(x_i, x_j)|\sigma_i^2, x_i, m] = -\left(f(0) + \mu_i x_i\right)^2 - \sigma_i^2 x_i + \gamma\left(f(0) + \mu_i x_i\right)E_i[f_j(x_j)|m]$$

As the second-order condition is always satisfied, I can write the best-response function of division i's manager, given type σ_i^2, as follows

$$x_i = x_i^0(\sigma_i^2) + \frac{\gamma}{2\mu_i}E_i[f_j(x_j)|m] \tag{39}$$

whenever positive. The best-response function clearly depends on the expectation that division i's manager has about the outcome of innovation in division j. As $E_i[f_j(x_j)|m] =$

[37] Recall that $\Sigma_i^{N_i}(B_i) = Var(\sigma_i^2)$ if $N_i = 1$.

$E_i\left[E_i[f_j(x_j)|m,x_j]|m\right] = E_i[f(0)+\mu_j x_j|m]$, taking expectations with respect to the information available to division j, I obtain for $i=1,2$ and $i \neq j$,

$$E_j[x_i|m] = -\frac{2-\gamma}{2}\frac{f(0)}{\mu_i} - \frac{E_j[\sigma_i^2|m]}{2\mu_i^2} + \frac{\gamma}{2}\frac{\mu_j}{\mu_i}E_j\left[E_i[x_j|m]\right|m] \tag{40}$$

Given that all the information is contained in the same message m, $E_j\left[E_i\left[\sigma_j^2|m\right]\middle|m\right] = E_i\left[\sigma_j^2|m\right]$ for $i=1,2$ and $i \neq j$, then repeated substitution gives,[38]

$$\begin{aligned} x_i^D(\sigma_i^2|\nu_i,\nu_j) &= x_i^0(\sigma_i^2) - \frac{\nu_j}{2\mu_i\mu_j}\sum_{n=0}^{+\infty}\left(\frac{\gamma}{2}\right)^{2n+1} - \frac{\nu_i}{2\mu_i^2}\sum_{n=1}^{+\infty}\left(\frac{\gamma}{2}\right)^{2n} \\ &= x_i^0(\sigma_i^2) - \frac{\gamma}{4-\gamma^2}\frac{\nu_j}{\mu_i\mu_j} - \frac{\gamma^2}{4-\gamma^2}\frac{\nu_i}{2\mu_i^2} \end{aligned} \tag{41}$$

If the equilibrium technologies are positive, it is readily checked that the technologies (41) form an equilibrium that is also the only one in which the division managers use strictly positive technologies. However, I still need to check that the technologies are strictly positive for any $\gamma < \Gamma$. To see this, note that

$$x_i^D(\sigma_i^2|\nu_i,\nu_j) > -\frac{f(0)}{\mu_i} - \frac{2}{4-\gamma^2}\frac{b_i}{\mu_i^2} - \frac{\gamma}{4-\gamma^2}\frac{b_j}{\mu_i\mu_j} \tag{42}$$

The right-hand side is positive if, and only if, $f(0) > -\frac{2}{4-\gamma^2}\frac{b_i}{\mu_i} - \frac{\gamma}{4-\gamma^2}\frac{b_j}{\mu_j}$. Recall from the definition of Γ that for any $\gamma < \Gamma$, $f(0) > -\frac{1}{1-\gamma^2}\frac{b_i}{2\mu_i} - \frac{\gamma}{1-\gamma^2}\frac{b_j}{2\mu_j}$. As $-\frac{1}{1-\gamma^2}\frac{b_i}{2\mu_i} - \frac{\gamma}{1-\gamma^2}\frac{b_j}{2\mu_j} > -\frac{2}{4-\gamma^2}\frac{b_i}{\mu_i} - \frac{\gamma}{4-\gamma^2}\frac{b_j}{\mu_j}$, it follows that the equilibrium technologies under decentralization are indeed strictly positive for any $\gamma < \Gamma$, regardless of the realization of riskiness parameters and posterior expectations.

I now show that there are no equilibria in which one of the division managers prefers to avoid innovation. Suppose by way of contradiction that such an equilibrium exists with division j's manager choosing no innovation, for a given message m. As division i's manager knows that $x_j^* = 0$, in equilibrium, then division i's optimal technology must be $x_i^* = x_i^0(\sigma_i^2) + \frac{\gamma}{2\mu_i}f(0)$ from (39). Given this technology, I can compute division j's expected profits for a given technology x_j as

$$E_j[\pi_j^\gamma(x_i^*,x_j)|\sigma_j^2,x_j,m] = -(f(0)+\mu_j x_j)^2 - \sigma_j^2 x_j + \gamma(f(0)+\mu_j x_j)\left[-\frac{\nu_i}{2\mu_i} + \frac{\gamma}{2}f(0)\right] \tag{43}$$

[38]The geometric series are well-defined because γ is positive and less than 1.

As we are in equilibrium and (43) is a concave function of x_j, it cannot be the case that the derivative of (43) with respect to x_j, computed at $x_j = 0$, is positive, that is, it must be the case that

$$\left.\frac{\partial E_j[\pi_j^\gamma(x_i^*, x_j)|\sigma_j^2, x_j, m]}{\partial x_j}\right|_{x_j=0} = -\mu_j f(0)\frac{4-\gamma^2}{2} - \sigma_j^2 - \gamma\frac{\mu_j}{\mu_i}\frac{\nu_i}{2} \leq 0 \tag{44}$$

or else division j's manager could increase the expected profits of his division by choosing a strictly positive technology. However, (44) holds if, and only if, $f(0) \leq -\frac{2}{4-\gamma^2}\frac{\sigma_j^2}{\mu_j} - \frac{\gamma}{4-\gamma^2}\frac{\nu_i}{\mu_i} < -\frac{2}{4-\gamma^2}\frac{b_j}{\mu_j} - \frac{\gamma}{4-\gamma^2}\frac{b_i}{\mu_i}$ but the opposite relationship holds for any $\gamma < \Gamma$. Thus, for any $\gamma < \Gamma$, there cannot exist equilibria in which one division manager avoids innovation. Similarly, there cannot be an equilibrium in which both division managers avoid innovation.

Finally, differentiating (41) with respect to $|\mu_i|$ gives

$$\frac{\partial x_i^D}{\partial|\mu_i|} = -\frac{1}{\mu_i^2}\left\{f(0) - \frac{\sigma_i^2}{|\mu_i|} - \frac{\gamma}{4-\gamma^2}\frac{\nu_j}{|\mu_j|} - \frac{\gamma^2}{4-\gamma^2}\frac{\nu_i}{|\mu_i|}\right\} \tag{45}$$

which is positive if, and only if, $|\mu_i| < \frac{(4-\gamma^2)\sigma_i^2+\gamma^2\nu_i}{(4-\gamma^2)f(0)-\gamma\frac{\nu_j}{\mu_j}}$ where the denominator is positive for any $\gamma < \Gamma$.

Proof of Theorem 1: Suppose that $[a_i, b_i] = [a_j, b_j]$. Given the expressions for total expected profits in (9) and (12) and focusing on the most informative communication equilibria under centralization, I can write the expected profit differential as,

$$\begin{aligned}\mu_j^2\left(\Pi^C - \Pi^D\right) =& \frac{\gamma^2}{1-\gamma^2}\frac{1}{z^2}\frac{E\left[\left(\sigma^2\right)^2\right]}{4} - \frac{1}{1-\gamma^2}\frac{1}{z^2}\frac{\Sigma_i(B_i)}{4} - \frac{\gamma^2(12-\gamma^2)}{(4-\gamma^2)^2}\frac{1}{z^2}\frac{\left(\bar{\sigma}^2\right)^2}{4} \qquad (46)\\ &+ \frac{\gamma^2}{1-\gamma^2}\frac{E\left[\left(\sigma^2\right)^2\right]}{4} - \frac{1}{1-\gamma^2}\frac{\Sigma_j(B_j)}{4} - \frac{\gamma^2(12-\gamma^2)}{(4-\gamma^2)^2}\frac{\left(\bar{\sigma}^2\right)^2}{4}\\ &+ \left[\frac{\gamma}{1-\gamma^2} - \frac{16\gamma}{(4-\gamma^2)^2}\right]\frac{1}{z}\frac{(\bar{\sigma}^2)^2}{2} \qquad (47)\\ &\equiv H(z;\gamma) \qquad (48)\end{aligned}$$

where $z \equiv \left|\frac{\mu_i}{\mu_j}\right|$. Note that $\left.\left(\Pi^C - \Pi^D\right)\right|_{\gamma=0} = H(z;\gamma)|_{\gamma=0} = 0$.[39] Next, let $z_1 > z_2$, define $F(\gamma) = H(z_1;\gamma) - H(z_2;\gamma)$ and note that $F(0) = 0$. As the residual variances are differen-

[39]For this to be the case, I need that $\lim_{\gamma\to 0}\Sigma_i(B_i) = 0$, $i = 1, 2$, that is, that truthful communication occurs when $\gamma = 0$. As I already argued at the beginning of Section 3, there does exist such an equilibrium when $\gamma = 0$.

tiable except at a countable number of points, differentiating F with respect to γ whenever both $\Sigma_i(B_i)$ and $\Sigma_j(B_j)$ are differentiable gives,[40]

$$\begin{aligned} F'(\gamma) =& \frac{d}{d\gamma}\left[\frac{\gamma^2}{1-\gamma^2}\right]\frac{E[(\sigma^2)^2]}{4}\left(\frac{1}{z_1^2}-\frac{1}{z_2^2}\right) - \frac{d}{d\gamma}\left[\frac{1}{1-\gamma^2}\right]\left(\frac{1}{4z_1^2}\Sigma_i(B_i;z_1) - \frac{1}{4z_2^2}\Sigma_i(B_i;z_2)\right) \\ & - \frac{1}{4(1-\gamma^2)}\left(\frac{1}{z_1^2}\frac{d\Sigma_i(B_i;z_1)}{d\gamma} - \frac{1}{z_2^2}\frac{d\Sigma_i(B_i;z_2)}{d\gamma}\right) - \frac{d}{d\gamma}\left[\frac{\gamma^2(12-\gamma^2)}{(4-\gamma^2)^2}\right]\frac{(\bar{\sigma}^2)^2}{4}\left(\frac{1}{z_1^2}-\frac{1}{z_2^2}\right) \\ & - \frac{1}{4(1-\gamma^2)}\left(\frac{d\Sigma_j(B_j;z_1)}{d\gamma} - \frac{d\Sigma_j(B_j;z_2)}{d\gamma}\right) + \frac{d}{d\gamma}\left[\frac{\gamma}{1-\gamma^2} - \frac{16\gamma}{(4-\gamma^2)^2}\right]\frac{(\bar{\sigma}^2)^2}{2}\left(\frac{1}{z_1}-\frac{1}{z_2}\right) \end{aligned} \tag{49}$$

Taking the limit as $\gamma \to 0$ gives

$$\begin{aligned} \lim_{\gamma\to 0} F'(\gamma) =& -\frac{1}{4}\left(\frac{1}{z_1^2}\lim_{\gamma\to 0}\frac{d\Sigma_i(B_i;z_1)}{d\gamma} - \frac{1}{z_2^2}\lim_{\gamma\to 0}\frac{d\Sigma_i(B_i;z_2)}{d\gamma}\right) \\ & -\frac{1}{4}\left(\lim_{\gamma\to 0}\frac{d\Sigma_j(B_j;z_1)}{d\gamma} - \lim_{\gamma\to 0}\frac{d\Sigma_j(B_j;z_2)}{d\gamma}\right) \end{aligned} \tag{50}$$

In order to complete the proof, I need to show that the derivative of each residual variance with respect to γ not only exists almost everywhere but that it admits a well-defined limit as $\gamma \to 0$. From Lemma B1 in Alonso, Dessein, and Matouschek (2012), it follows that $\Sigma_i(B_i; z)$ and $\Sigma_j(B_j; z)$ are absolutely continuous functions of γ in a right neighborhood of $\gamma = 0$ and following their same steps I can compute $\lim_{\gamma\to 0}\frac{d\Sigma_i(B_i;z)}{d\gamma} = \frac{(b_i-a_i)(b_j+a_j)}{12}z > 0$ and $\lim_{\gamma\to 0}\frac{d\Sigma_j(B_j;z)}{d\gamma} = \frac{(b_j-a_j)(b_i+a_i)}{12}\frac{1}{z} > 0$.[41] Thus, given that $a_i = a_j$ and $b_i = b_j$, it follows that

$$\lim_{\gamma\to 0} F'(\gamma) = \frac{z_1 - z_2}{z_1 z_2}\frac{b^2-a^2}{24} \tag{52}$$

which is positive by $z_1 > z_2$. As F is continuous everywhere and differentiable except at countably many points, it is Henstock-Kurzweil integrable and a more general version of the

[40]From now on, I will slightly abuse notation and write $\Sigma_i(B_i; z)$ to highlight which value of z is considered.

[41]For a heuristic derivation, recall from (33) that $\bar{N}_i \approx \sqrt{\frac{b_i-a_i}{2B_i}}$ in the limit, as $\gamma \to 0$. Thus, from (8), I have that

$$\Sigma_i(B_i) \approx \frac{b_i-a_i}{3}B_i - \frac{B_i^2}{3} \Longrightarrow \lim_{\gamma\to 0}\frac{d\Sigma_i(B_i)}{d\gamma} = \frac{(b_i-a_i)(b_j+a_j)}{12}z. \tag{51}$$

A similar analysis can also be used to show that $\lim_{\gamma\to 0}\frac{d(\Pi^C-\Pi^D)}{d\gamma} = -\frac{1}{4\mu_i^2}\lim_{\gamma\to 0}\frac{d\Sigma_i(B_i)}{d\gamma} - \frac{1}{4\mu_j^2}\lim_{\gamma\to 0}\frac{d\Sigma_j(B_j)}{d\gamma} < 0$, which implies that decentralization is always better than centralization for small values of γ.

fundamental theorem of calculus implies that $F(\gamma) = \int_0^\gamma F'(y)dy$. Given that $\lim_{\gamma\to 0} F'(\gamma) > 0$, there exists $\epsilon > 0$ such that $F(\gamma) = H(z_1;\gamma) - H(z_2;\gamma) > 0$ for any $\gamma \in (0,\epsilon)$. Finally, notice that the argument is independent of the magnitude of z_1 and z_2. This shows that a technological shock which increases the productivity gap between division i and division j (where i is initially weaker) increases the relative attractiveness of centralization.

Proof of Proposition 5: As the residual variances are differentiable except at a countable number of points, differentiating H with respect to z whenever both $\Sigma_i(B_i)$ and $\Sigma_j(B_j)$ are differentiable, gives

$$\frac{\partial H(z;\gamma)}{\partial z} = -\frac{\gamma^2}{1-\gamma^2}\frac{1}{z^3}\frac{E\left[\left(\sigma^2\right)^2\right]}{2} + \frac{1}{1-\gamma^2}\frac{1}{z^3}\frac{\Sigma_i(B_i)}{2} - \frac{1}{4(1-\gamma^2)}\frac{1}{z^2}\frac{d\Sigma_i(B_i)}{dz} - \frac{1}{1-\gamma^2}\frac{1}{4}\frac{d\Sigma_j(B_j)}{dz} + \frac{\gamma^2(12-\gamma^2)}{(4-\gamma^2)^2}\frac{1}{z^3}\frac{(\bar{\sigma}^2)^2}{2} - \left[\frac{\gamma}{1-\gamma^2} - \frac{16\gamma}{(4-\gamma^2)^2}\right]\frac{1}{z^2}\frac{(\bar{\sigma}^2)^2}{2} \tag{53}$$

From (35) and (36), it follows that $-\frac{1}{4(1-\gamma^2)}\frac{1}{z^2}\frac{d\Sigma_i(B_i)}{dz}\Big|_{z=1} = -\left[-\frac{1}{1-\gamma^2}\frac{1}{4}\frac{d\Sigma_j(B_j)}{dz}\Big|_{z=1}\right]$ because $B_i = B_j = \gamma\frac{\bar{\sigma}^2}{2} \equiv B$ when $z = 1$. Thus,

$$\left.\frac{\partial H(z;\gamma)}{\partial z}\right|_{z=1} = \frac{1}{2(1-\gamma^2)}\left\{\Sigma(B) - \gamma^2 E\left[\left(\sigma^2\right)^2\right]\right\} + \left[\frac{16\gamma + 12\gamma^2 - \gamma^4}{(4-\gamma^2)^2} - \frac{\gamma}{1-\gamma^2}\right]\frac{(\bar{\sigma}^2)^2}{2} \tag{54}$$

Next, recall that $\Sigma(B) \leq Var(\sigma^2)$ and $E\left[\left(\sigma^2\right)^2\right] = Var(\sigma^2) + (\bar{\sigma}^2)^2$, thus

$$\left.\frac{\partial H(z;\gamma)}{\partial z}\right|_{z=1} \leq \frac{Var(\sigma^2)}{2} + \left[\frac{16\gamma + 12\gamma^2 - \gamma^4}{(4-\gamma^2)^2} - \frac{\gamma}{1-\gamma}\right]\frac{(\bar{\sigma}^2)^2}{2} \tag{55}$$

and the right-hand side is negative if, and only if,

$$D(\gamma) = \frac{\gamma}{1-\gamma} - \frac{16\gamma + 12\gamma^2 - \gamma^4}{(4-\gamma^2)^2} > \frac{1}{3}\left(\frac{b-a}{b+a}\right)^2 \tag{56}$$

As $D(\gamma)$ is continuous in γ over $[0,1)$, $D(0) = 0$ and $\lim_{\gamma\to 1} D(\gamma) = +\infty$, there exist parametrizations such that for some $\hat{\gamma} \in (0,\Gamma)$, $D(\hat{\gamma}) > \frac{1}{3}\left(\frac{b-a}{b+a}\right)^2$ which implies that $\left.\frac{\partial H(z;\hat{\gamma})}{\partial z}\right|_{z=1} < 0$.

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