Eavesdropping and Innovation

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Abstract

Innovation often requires completing a series of steps, some of which are unmarketable and unpatentable. The first firm to complete all these steps profits either from a first-mover advantage or from patented components of the final product. Less innovative firms, unable to complete some of these steps, may resort to espionage to learn the missing steps and advance the development of their final product. We show that larger market rewards (e.g., stronger patents) or more efficient experimentation can harm innovation under espionage. We also investigate the role of a rival's acquisition, third-party hackers, and different espionage methods.

Keywords: espionage, innovation, research, development, experimentation, patents

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1 Introduction

Throughout history, inventors have used secrecy to protect their inventions. Rivals, unable to figure out a secret, have often used espionage, which has had a tremendous impact on the economy. For instance, China's silk monopoly ended in 552 AD when two monks smuggled silkworms' eggs from China to the Byzantine Empire.[1] China's tea monopoly ended in the 1800s when Robert Fortune supplied smuggled tea from China to Europe.[2] Economic espionage also catapulted the American industrial revolution. In the 1800s, Great Britain used secrecy to protect its superior spinning and weaving machines. Francis Cabot Lowell and Samuel Slater spent time with these machines, memorized their design, and built their own versions after returning to the U.S.[3]

Today, economic espionage is at the forefront of concerns for innovative companies. China's theft of trade secrets is estimated to cost the U.S. over 300 billion per year.[4] Around 73 percent of the 1,485 spies caught on U.S. soil from 1990-2019 engaged in economic espionage (Nowrasteh, 2021).[5] Spies use a myriad of methods steal secrets, including infiltrating a rival firm (e.g., cleaning staff), planting a bug (e.g., cyber espionage), or one-time breaches (Melton, 2015). For instance, the company 'Four Pillars' paid $160,000 over eight years to a senior research engineer working for its competitor 'Avery Dennison' to obtain research documents and secret adhesive formulas.[6]

We present a framework to investigate the impact of espionage on innovation, acknowledging that innovation is an uncertain, multi-stage process: patents or copyrights cannot protect the results of some of these stages and secrecy is the only alternative to protect them. For instance, testing data, a central input to develop a patentable invention, may fail to meet the patentability standard. In our model, the innovation process consists of two stages. The outcome of the first stage (the 'breakthrough') cannot be protected by a patent. The outcome second stage (the 'final product') is patentable, and the first firm to patent it appropriates monopoly profits.[7] There are two firms. Firm A can work on the two stages (research and

[1]See, for example, Nickisch (2016). Supplying silk to Europe became a vital component of the Byzantine Empire's economy for the next 650 years.

[2]https://www.npr.org/sections/thesalt/2015/03/10/392116370

[3]https://www.history.com/news/industrial-revolution-spies-europe

[4]https://www.theguardian.com/world/2020/feb/06/china-technology-theft-fbi-biggest-threat

[5]This statistic does not include remote espionage attempts from individuals who never set foot on U.S. soil. Moreover, firms report only a small fraction of commercial espionage cases because it is not in their best interest to publicize vulnerabilities (Barrachina et al., 2021).

[6]https://www.nytimes.com/1999/04/30/business/two-convicted-in-spying-case.html. The spy was discovered by chance by a former employee of Four Pillars (legitimately) hired by Avery Dennison.

[7]Bhattacharya and Guriev (2006) also studies a two-stage model of cumulative R&D in which the first

development), but firm B can only work on the second one (development). In other words, firm A is the only firm that can make a non-patentable breakthrough, but both firms can develop the final product conditional on having the breakthrough.

In our baseline model, the espionage method is 'infiltration,' whereby firm B either plants 'a bug' in the computers, or hires an insider, as in the Four Pillars/Avery Dennison case. Firm B makes a one-time investment to increase the probability of infiltrating firm A. If it succeeds, it learns, in real-time, all the information observed by firm A.[8] Until Section 8, we assume that infiltration is undetectable, capturing that modern cybersecurity espionage is difficult to detect. For instance, some botnets communicate information in real-time, persistently and anonymously, and can self-destruct without a trace after obtaining the desired information (Bederna and Szadeczky, 2020).

Initially, firm A is uncertain about the feasibility of the breakthrough. Firm A experiments until its belief that the breakthrough is feasible is sufficiently low. Furthermore, its incentive to experiment hinges on its expected continuation payoff, which depends on how likely firm A believes that firm B is spying on it. In equilibrium, when firm B's espionage effort is high, and firm A stops experimentation earlier because it correctly believes that espionage is likely. This makes a breakthrough is less likely to occur, which reduces firm B's incentives to spy. Firm A's experimentation effort and firm B's espionage effort are jointly determined in equilibrium.

We show that policies that offer higher appropriation for the final product (e.g., stronger patents) can *reduce* innovation, by making firm A stop experimentation earlier. All else equal, a larger reward encourages firm A to experiment longer and, hence, a breakthrough is more likely to occur. These forces combined increase firm B's incentives to spy. But when firm B's espionage effort increases, firm A's incentive to experiment decreases because in expectation there is more competitive pressure during the development stage. We show that, in equilibrium, more espionage can overwhelm the positive impact of stronger patents on experimentation and, hence, stronger patents can *reduce* innovation. This result complements the literature on patent policy when innovation is sequential. Bessen and Maskin (2009), for example, show that stronger patents may discourage sequential and complementary innovation, when the innovator benefits from complementary inventions by an imitator. Our model features sequential and complementary innovation—a breakthrough is required for the final product—and we also show that stronger patents may reduce innovation. However,

stage has no value to consumers and the second stage develops a marketable product.

[8] Related to this assumption, Solan and Yariv (2004) study two-players games where one of the players makes a one-time investment in spying on his opponent.

our economic mechanism does not hinge on the imitator's innovation. Instead, the channel that makes stronger patents less desirable is their impact on espionage effort.

Espionage is inefficient because firm A experiments less and firm B spends resources trying to infiltrate A. In situations where firm A knows the identify of firm B, one possible solution is to allow firm A to acquire firm B, as long as the acquisition is permitted by antitrust authorities. An acquisition increases firm A's payoff for two reasons. First, it removes the espionage threat by firm B. Second, it grants firm A access to an additional development technology, which could enhance firm A's development capabilities. We find firm A'a acquisition price, and characterize when the acquisition motive is to prevent espionage only or to also enhance A's development technology.

We then investigate the role of espionage by third-party hackers rather than rivals. Assuming that the hacker can commit to trade with only one of the firms, we find that firm A innovates more with third-party hackers than with rival's spies. That is, competition between the firms for trading with the hacker (firm A to prevent the secret from leaking, the firm B to obtain the secret) makes secrecy more effective. The key for this result is that trade with the hacker can occur only after the breakthrough has occurred. At this point, if firm B has the highest willingness to pay for the secret, then it is sequentially rational to pay at most firm A's willingness to pay. This "low" price hampers the hacker's ex-ante incentives to spy. On the other hand, if firm A has the highest willingness to pay, the hacker's espionage incentive is identical to firm B in the baseline case. However, firm A now benefit from reducing competition in the development stage.

Lastly, we explore a different espionage method. Rather than silently spying on firm A from time 0, and observe A's information from then on, we explore the espionage dynamics when firm B can access A's information only once, for only one instant. In this alternative espionage model, firm B chooses the *timing* of espionage. Firm B does not want to spy too early—probably there is nothing to steal at this point—nor does it want to spy too late—firm A already reached the market. Equilibrium strategies involve mixing: Firm B chooses an espionage time in an interval bounded away from zero. Firm A experiments at "full speed" for times outside this interval, and at "moderate speed" while in this interval.

2 Related literature

Hall et al. (2014) surveys the literature and find that most innovative companies rely on secrets, rather than patents, to protect their inventions. Anton and Yao (2004) study the decision of partially disclosing (in a patent) a cost-reducing innovation or keeping it secret. They show that firms patent minor improvements but keep significant ones secret to signal a cost advantage and deter competitors. Bessen (2005) studies the choice between patents and secrecy under the threat of imitation. In contrast to these papers, the first invention in our model is unpatentable, so secrecy is the only protection mechanism. Erkal (2005) studies a two-stage model where firms decide to patent the first invention or to keep it secret. As in our model, the second one hinges on inventing the first one. Secrecy forces competitors to re-invent the first invention, while in our model, the rival uses espionage to gain access to the first invention. Bar (2006) studies secrecy decisions with multi-stage inventive steps and patenting requires sufficient distance to the status quo. Front-runners avoid publishing their results, but laggards publish incremental results to change the status quo and prevent front-runners from patenting. In contrast to our model, all firms can develop the first innovation, and all inventions are known to be feasible and patentable.

The experimentation in our model relates to Akcigit and Liu (2016), where two firms choose between a safe research line or a risky but more promising one. Firms do not observe whether their rival knows whether the risky line is a dead-end. Competition pushes firms to switch to the safe line too early from an efficiency point of view. In our model, the firm experimenting does not know if the rival is spying on it, hindering experimentation incentives.

In Hopenhayn and Squintani (2016) firms first need to make a breakthrough and then decide how long to improve the invention before patenting it. Competition pushes firms to patent too early, which leads to inefficiently low-quality inventions. Bobtcheff et al. (2017) generalizes these results by allowing for arbitrary breakthrough distributions and time-dependent payoffs. Similar to our model, in Song and Zhao (2021) the feasibility of the first innovation is uncertain, and the second one is certainly feasible. The first firm to finish the first stage chooses whether to disclose this result. Disclosure allows firms to appropriate payoffs in both stages. Firms disclose the first-stage result only if they discover it quickly to manipulate the rival's belief about the feasibility of the first stage. Firms have no incentives to disclose information in our model, but rivals can access it through espionage.

In Barrachina et al. (2014) an incumbent knows the rival is spying on it to decide whether to enter the market. Espionage produces a noisy signal about the incumbent's cost. The incumbent can benefit from espionage by signal-jamming. In Barrachina et al. (2021), in addition to noisy espionage, the entrant uses the incumbent's past prices as a noisy signal for demand. Both of these papers argue that espionage may increase market competition. In our model, the 'entrant' is privately informed about the precision of the signal (it is perfect or non informative). In contrast to these papers, entry is feasible only after the 'incumbent' makes a breakthrough.

Henry and Ruiz-Aliseda (2016) study the dynamics of secret keeping, where firms know a secret, and must pay a cost to preserve it, and other firms can spy to learn it. Outsiders anticipate that the secret will eventually be unprotected, so they want to free ride and avoid paying the espionage cost. The equilibrium path features entry of some outsiders, who protect the secret, a waiting period with no entry, and eventually unprotected entry. In Henry and Ponce (2011), two firms can either imitate (at a cost) or buy a license from the innovator. The main insight is that a license that permits resale of knowledge, priced at the imitation cost, is optimal. The reason is that the innovator and the first licensee will compete aggressively to license to the remaining firm, so the first licensee pays a positive price and the second one gets a free license. Thus, none of the firms wants to be the first licensee, so, in equilibrium, there is licensing delay, which is profitable for the inventor. Here, espionage is not an option.

3 The model

There are two firms, denoted by $i \in \{A, B\}$, competing to bring a new *product* to the market. The first firm to do so gets a payoff of $\pi > 0$, while the other firm gets zero.

The new product must incorporate a non-patentable novel *technology*, and only firm A has the research capability to create it. However, it is uncertain whether it is feasible to create this new technology. If it is unfeasible (denoted by $\theta = 0$), it will never be created and none of the firms will be able to develop the product. If it is feasible (denoted by $\theta = 1$), a breakthrough arrives stochastically depending on firm A's research investment, but firm A could give up before a breakthrough arrives. Once the technology is created, it is certainly possible to create the new product after waiting a stochastic development delay.

The game ends either when one of the firms has brought the product to the market or when firm A gives up trying to create the new technology.

At time $t = 0$, the firms share a common belief p_0 that the new technology is feasible, i.e. $p_0 = \Pr(\theta = 1 | t = 0)$. Firm A has one unit of research and decides how much, and for how long, to spend to create the new technology. When investing $x_t \in [0, 1]$, firm A incurs the flow cost kx_t and a breakthrough arrives with flow probability $\eta\theta x_t$, where $k > 0$ is the unit flow cost of experimentation and $\eta > 0$ is the arrival rate of a breakthrough per unit of investment conditional on a feasible technology. The longer firm A invests without observing a breakthrough, the more pessimistic it becomes about the likelihood that the new technology is feasible. Conditional on an investment history $(x_\tau)_{\tau=0}^t$, firm A's belief at time t that the new technology is feasible, p_t, is:

$$\Pr(\theta = 1|(x_\tau)_{\tau=0}^t) \equiv p_t = \frac{p_0 e^{-\eta \int_0^t x_s \mathrm{d}s}}{p_0 e^{-\eta \int_0^t x_s \mathrm{d}s} + 1 - p_0}.$$

Firm A privately observes its flow investment x_t and the occurrence of a breakthrough. Firm B cannot create the new technology but can develop the new product if it learns about it. Firm i's flow cost to develop the product is c_i, and by paying this flow cost, the development of the product is completed at flow rate $\lambda_i\theta$.

To learn about the new technology firm B relies on "espionage." The espionage technology in our baseline model consists of an undetectable infiltration at time $t = 0$ (e.g. undetectable bot), which allows firm B to learn, in real-time, everything that firms A knows about the new technology. Firm B can only infiltrate firm A at time $t = 0$, and at this time it privately invests a lump-sum amount to increase the probability of infiltration.

Time is continuous and both firms discount the future at rate $r > 0$.

3.1 Analysis

We start by computing the firms' payoffs in two development scenarios: (1) Firm A is the only one developing the product; (2) Firms A and B are both developing the product.

Proposition 1. *Let $c_i < \lambda_i\pi$. At the beginning of the development stage:*

1. *If firm A is the only firm developing, its expected payoff is:*

$$V_A^L = \frac{\lambda_A\pi - c_A}{r + \lambda_A}.$$

2. *If both firms are developing, the expected payoff of firm i is:*

$$V_i^C = \frac{\lambda_i\pi - c_i}{r + \lambda_A + \lambda_B}.$$

Under the assumption $c_i < \lambda_i \pi$, both firms invest in development until one of the firms brings the product to the market.

Competition reduces the payoff of firm A. In fact, the ratio of payoffs when firm A is the only developer and the payoff under competition is:

$$\frac{V_A^L}{V_A^C} = 1 + \frac{\lambda_B}{r + \lambda_A} > 1.$$

The possibility of espionage creates uncertainty regarding the competition during the development stage: firm A does not know whether it is the only firm developing the product, conditional on having created the new technology. Firm A believes that with probability $\mu \in [0, 1]$ that firm B has infiltrated (although it cannot prove it), in which case firm A would face competition during the development stage.

Conditional on μ, firm A's expected payoff after creating the new technology is:

$$V_A(\mu) = \mu V_A^C + (1 - \mu) V_A^L. \tag{1}$$

This payoff is time independent and strictly decreasing in μ. That is, the larger the probability that B infiltrated A, the lower the payoff for firm A because of the competitive pressure during development.

Experimentation by firm A**.** At time 0, firm A believes the new technology is feasible with probability p_0. Taking both p_0 and μ as given, firm A decides how much of its research capacity (normalized to 1), and for how long, to invest in the creation of the new technology. That is, at each $t \geqslant 0$ firm A chooses $x_t \in [0, 1]$.

In this dynamic problem, the state variable that determines whether firm A will continue or stop experimenting is the belief that the new technology is feasible. Fixing firm B's infiltration probability μ, let $W_A(p)$ be firm A's value function when the belief of a viable breakthrough is p. The Hamilton-Jacobi-Bellman equation for $W(\cdot)$ is:

$$rW_A(p) = \max_{x \in [0,1]} \left[-k + \eta p (V_A(\mu) - W_A(p)) - \eta p (1 - p) W_A'(p) \right] x. \tag{2}$$

This equation has a unique solution, from which we obtain the following result.

Proposition 2. *Firm A invests all its research capacity at time t if and only if* $p_t \geqslant \bar{p}(\mu)$, *where:*

$$\bar{p}(\mu) = \frac{k}{\eta V_A(\mu)}. \tag{3}$$

Furthermore, $\bar{p}(\cdot)$ is increasing. Firm A's value function is

$$W_A(p) = \begin{cases} 0 & \text{if } p \leqslant \bar{p}(\mu) \\ \frac{\eta p (r V_A(\mu)+k)}{r(\eta+r)} - \frac{k}{r} - \left(\frac{\eta \bar{p}(\mu)(r V_A(\mu)+k)}{r(\eta+r)} - \frac{k}{r}\right)\left(\frac{1-p}{1-\bar{p}(\mu)}\right)^{\frac{\eta+r}{\eta}} \left(\frac{\bar{p}(\mu)}{p}\right)^{\frac{r}{\eta}} & \text{if } p > \bar{p}(\mu) \end{cases} \tag{4}$$

which is increasing in p, for $p > \bar{p}(\mu)$.

The solution in Proposition 2 is intuitive: Firm A experiments only if it is sufficiently optimistic that creating the new technology is feasible. The comparative static results are also intuitive. Firm A: (1) experiments less when experimenting is more costly ($\bar{p}$ increases in k); (2) experiments more when creating the new technology, conditional on being feasible, occurs faster ($\bar{p}$ decreases in η); (3) experiments less when it believes infiltration is more likely ($\bar{p}$ increases in μ); (4) experiments more when there is a larger reward for creating the product ($\bar{p}$ decreases in π, through $V_A(\mu)$).

The fact that firm A stops experimenting earlier when μ is larger reflects the standard of underappropriation externality: when infiltration is more likely, higher μ, firm A does not capture the full return of experimentation, which decreases the incentive to experiment.

Infiltration investment by firm B. Given $\bar{p} \in [0, 1]$ as the threshold belief at which firm A stops experimenting, firm B decides how much to invest to infiltrate firm A. The next proposition characterizes the value of espionage for any given threshold $\bar{p} \leqslant p_0$.

Proposition 3. *Let $\bar{p} \geqslant p_0$ be the threshold belief at which firm A stops experimenting. Firm B's expected payoff from successfully infiltrating firm A is:*

$$W_B(\bar{p}) = p_0 V_B^C \frac{\eta}{\eta + r}\left(1 - \left(\frac{1-p_0}{p_0}\right)^{\frac{\eta+r}{\eta}} \left(\frac{1-\bar{p}}{\bar{p}}\right)^{-\frac{\eta+r}{\eta}}\right). \tag{5}$$

Furthermore, $W_B(\cdot)$ is decreasing.

Espionage is more valuable when the breakthrough is ex-ante more likely (larger p_0), firm A experiments longer (lower $\bar{p}$), or the market reward is larger (larger V_B^C).

Firm B can infiltrate firm A with probability μ at cost $c(\mu)$, which is strictly increasing and convex. Therefore, conditional on the parameter $\bar{p}$, firm B chooses the infiltration probability that solves:

$$\max_{\mu \in [0,1]} \quad \mu W_B(\bar{p}) - c(\mu). \tag{6}$$

Proposition 4. *The optimal infiltration probability, for any given threshold belief $\bar{p}$, is given by the solution to (6). At an interior solution, the optimal infiltration probability is:*[9]

$$\mu(\bar{p}) = [c']^{-1}(W_B(\bar{p})). \tag{7}$$

Furthermore, in this case, $\mu(\cdot)$ is strictly decreasing.

Equilibrium. We now provide a formal definition of the equilibrium in this game. Note that firm A never observes the actions of firm B, unless firm B ends the game by developing first. Firm B makes a one-time decision at the beginning of the game when it chooses the infiltration probability. Therefore, the equilibrium concept is Nash equilibrium.

Definition 1. *An equilibrium is a pair $(\bar{p}^*, \mu^*)$ that is a fixed point of the system of (3) and (7); Given μ^*, firm A's equilibrium experimentation strategy is characterized in Proposition 2; during the development stage, any firm that knows the new technology invest until one of the firms brings the product to the market.*

To find the equilibrium values of $\bar{p}^*$ and μ^*, we use firm A and B's best responses in (3) and (7), respectively.

Proposition 5 (Existence and Uniqueness)**.**
When $\bar{p}(0) < p_0$, there exists a unique equilibrium, which is interior, i.e., $\bar{p}^* \in (0, p_0)$ and $\mu^* \in (0, 1)$.

Proof. At $\bar{p} = p_0$, $W_B(\bar{p}) = 0$ and $\mu(\bar{p}) = 0$. For all $\bar{p} \in (0, p_0)$, Proposition 4 predicts a strictly decreasing $\mu(\cdot)$ that is continuous at $\bar{p} = p_0$. As $\bar{p} \to 0$, we have $W_B \to p_0 V_B^C \frac{\eta}{\eta + r}$ and $\lim_{\bar{p} \to 0} \mu(\bar{p}) < 1$. On the other hand, $\bar{p}(0) < p_0$ by assumption, and Proposition 2 predicts a strictly increasing $\bar{p}(\cdot)$. By Intermediate value theorem, there exists a unique intersection of $\mu(\bar{p})$ and $\bar{p}(\mu)$ for some $\mu^* \in (0, \lim_{\bar{p} \to 0} \mu(\bar{p}))$ and $\bar{p}^* \in (\bar{p}(0), p_0)$. □

Figure 1 shows the firms' best responses and their intersection, which determines the equilibrium values of $\bar{p}^*$ and μ^*.

[9] If the cost function satisfy the Inada condition, the solution is interior.

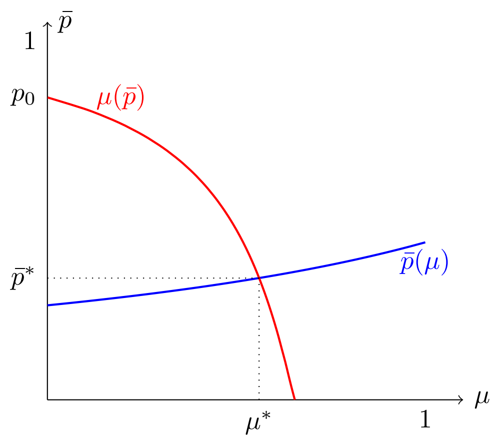

Figure 1: Firm A's best response $\bar{p}(\cdot)$ and firm B best response $\mu(\cdot)$. The figure also shows the equilibrium values p^* and μ^*, and the prior belief p_0.

4 Equilibrium Comparative Statics

The equilibrium comparative statics on the model parameters are intuitive from Figure 1. In each case, we examine how changing a parameter changes the best responses. For the sake of exposition we restrict to the case of an interior solution, so the infiltration probability is given by (7).

Increasing the market reward, π. An increase in π corresponds to more appropriation for the firm that first brings the new product to the market. For instance, the first firm to develop the product can patent it, in which case π captures the strength of patent protection. Alternatively, π can measure the value of having a first-mover advantage.

From (3), since $V_A(\mu)$ increases with π for any fixed μ, $\bar{p}(\cdot)$ decreases pointwise. Firm A is willing to experiment longer when the market reward for developing the new product is higher. Since V_B^C also increases with π, $W_B(\cdot)$ increases pointwise, which implies that $\mu(\cdot)$ in (7) increases pointwise. Firm B has stronger incentives to infiltrate firm A because the payoff from winning the development race is higher. This incentive is reinforced by A's willingness to experiment longer for any fixed μ, which implies that μ^* increases in equilibrium. The effect on $\bar{p}^*$, however, is *ambiguous* because infiltration is more likely and this counteracts the positive effect of a larger market reward, π. Thus, higher market reward could deter or encourage innovation.

Proposition 6. *A larger market reward: (1) increases the equilibrium infiltration probability;*

(2) encourages experimentation if and only if:

$$\frac{\partial V_A(\mu^*)}{\partial \pi} > ([c']^{-1})'(W_B(\bar{p}^*))\frac{W_B(\bar{p}^*)}{V_B^C}(V_A^L - V_A^C). \tag{8}$$

Condition (8) in Proposition 6 compares firm A's gain from a larger reward (left-hand side) conditional to the loss from increased competition due to higher infiltration effort by firm B (right-hand side). When this condition holds, the gain outweighs the loss and therefore the threshold to stop experimentation, $\bar{p}^*$, decreases. Figure 2 shows a numerical example where condition (8) holds. In the figure, there is a non-monotone relationship between the market reward and the equilibrium threshold belief for experimentation. Higher market reward can lead to less experimentation.

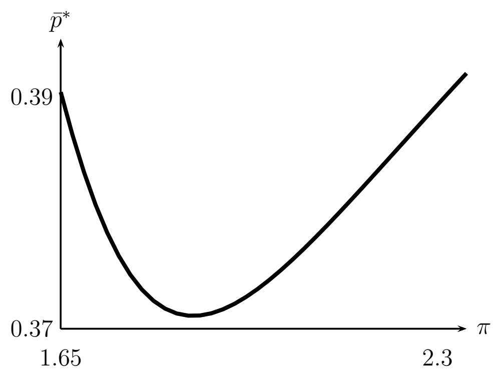

Figure 2: Non-monotone relationship between the market reward, π, and the equilibrium threshold belief for experimentation, $\bar{p}^*$. Model parameters: $k = 0.3$; $\eta = 1$; $p_0 = 0.5$; $r = 1$; $\lambda_A = 1$; $\lambda_B = 1$; $c_A = 0.1$; $c_B = 0.1$; $c(\mu) = 0.1\mu^{1.1}$

Increasing λ_B. An increase in λ_B means a faster development speed by firm B, conditional on knowing the new technology. Fixing the infiltration probability, Firm A stops experimenting earlier because of the higher competitive pressure during the development stage. Firm B tries harder to infiltrate because it is faster at development, so it benefits more from knowing the new technology. These two effects—more competition at the development stage and higher incentives to infiltrate—make firm A less willing to experiment. The effect on higher λ_B on the infiltration probability, μ^*, however, is ambiguous because less experimentation by firm A reduces the incentive to infiltrate firm A.

Increasing λ_A. An increase in λ_A means that firm A can develop the product faster, conditional on having created the new technology.

Fixing the infiltration probability, Firm A experiments longer because its is more likely to win the development race. Firm B benefits less from infiltrating A because it is less likely to win the development race. This effect makes firm A's even more willing to experiment longer. The infiltration probability, μ^*, however can increase or decrease because more experimentation by firm A increases B's incentives to infiltrate but this is counteracted by B's smaller chances of winning the development race.

Decreasing η. When η decreases, the technology is harder to discover conditional on being feasible.

Fixing the infiltration probability, Firm A experiments less because it becomes more difficult get a breakthrough, so Firm B's benefits less from infiltrating A. These countervailing effects mean that decreasing η has an ambiguous effect on experimentation and espionage.

Increasing k. When experimentation is more costly, firm A has less incentives to experiment. Firm B is not directly affected by k, but it is less willing to infiltrate because firm A experiment less.

We summarize all these comparative static results in the following proposition

Proposition 7. *We have the following comparative static results:*

1. *Faster development speed by any firm (larger λ_j) increases experimentation and has an ambiguous effect on espionage.*
2. *Lower rate of breakthroughs (lower η) has an ambiguous effect on both experimentation and espionage.*
3. *When experimentation is more costly (larger k) there is less experimentation and less espionage.*

5 Rival Acquisition

Whether the firms are willing to collaborate crucially depends on the nature of competition. For instance, during the second world war, the U.S. would have never offered a joint venture to make the atomic bomb to the Germans. Even today, the U.S. and China may not be willing to collaborate to develop military applications of new technologies such as Artificial Intelligence or Gene Editing. This is reflects a high value of having the technological advantage in a given field (first-mover advantage), which in our model is measured by π.

Moreover, collaboration depends on which contracts are legal, since agreements between competitors raise complex antitrust issues. If both firms agree to collaborate in creating the product but compete in the market after its creation, under intense market competition, e.g. Bertrand, profits will be driven to zero. Thus, collaboration is unprofitable. A contract establishing that only one of them will sell the product could create an antitrust violation.[10]

Another solution is to acquire a rival. Espionage reduces the firms' joint surplus: Firm A experiments less and firm B spends resources trying to infiltrate A. Therefore, if firm A knows the identity of the potential spy and an acquisition is lawful (equivalently, firms can sign a contract that prevent espionage), A will acquire B will do so. In many cases, however, it will be difficult for a firm to determine the identity of a potential the spy, especially when there are many competitors.

An acquisition increases Firm A's payoff for two reasons. First, there is no threat of espionage by firm B. Second, firm A has access to an additional development technology, which means that development could be faster. If a breakthrough occurs, Firm A can choose to use its own development technology, the development technology acquired from B, or both. The next proposition characterizes which development technology A will use if it acquires B.

Proposition 8. *Suppose firm A acquires firm B. Then, A will develop using both development technologies, developing at rate $\lambda_{aq} \equiv \lambda_A + \lambda_B$ and cost $c_{aq} \equiv c_A + c_B$ if and only if:*

$$r\pi > \max\left\{\left(\frac{\lambda_A + r}{\lambda_B}\right) c_B - c_A, \left(\frac{\lambda_B + r}{\lambda_A}\right) c_A - c_B\right\}. \tag{9}$$

Otherwise, it will use only one of the two development technologies. It will use its own, and develop at rate $\lambda_{aq} \equiv \lambda_A$ and cost $c_{aq} = c_B$, if $\pi r(\lambda_A - \lambda_B) \geqslant (\lambda_B + r)c_A - (\lambda_A + r)c_B$, and it will use B's technology, and develop at rate $\lambda_{aq} = \lambda_B$ and cost $c_{aq} = c_B$ otherwise.

Proposition 8 characterizes firm A's speed of development post acquisition, λ_{aq}, and its development cost, c_{aq}. Firm A's expected payoff at development stage post acquisition is:

$$V_{\text{aq}} = \frac{\lambda_{\text{aq}}\pi - c_{\text{aq}}}{r + \lambda_{\text{aq}}},$$

[10] https://www.ftc.gov/tips-advice/competition-guidance/guide-antitrust-laws/dealings-competitors

so it stops experimenting at the threshold belief:

$$\bar{p}^*_{\text{aq}} = \frac{k}{\eta V_{\text{aq}}}.$$

Since $V_{\text{aq}} \geqslant V_A(0) \geqslant V_A(\mu)$ for all $\mu \in [0,1]$, an acquisition increases firm A experimentation. Without the acquisition, firm A stops experimenting earlier because of the uncertain competitive threat during the development stage.

How much should firm A offer to acquire B? Suppose that A makes a take-it-or-leave it offer to buy firm B, before any investments have been made. If firm B rejects, A and B play the game described in Section 3. We define $W_A^{\text{aq}}(\cdot)$ as firm A's value from an acquisition. This value is given in (4), substituting $V_A(\mu)$ for V_{aq} and $\bar{p}(\mu)$ for $\bar{p}^*_{\text{aq}}$.

Firm A's optimal take-it-or-leave-it offer is:

$$Q^* = \mu^* W_B(\bar{p}^*) - c(\mu^*),$$

where $(\bar{p}^*, \mu^*)$ is the equilibrium in Section 3 (see Figure 1). The acquisition is always feasible because:

$$W_A^{\text{aq}}(p_0) - W_A(p_0) \geqslant Q^*. \tag{10}$$

When $\lambda_{\text{aq}} \in \{\lambda_A + \lambda_B, \lambda_B\}$, by acquiring firm B, firm A prevents espionage and improves its development technology. This happens with symmetric development technologies—i.e., when $\lambda_A = \lambda_B$ and $c_A = c_B$—because (9) reduces to $\lambda\pi > c$, which holds by assumption. It also happens with asymmetric technologies, when π is large enough or when π is small, (9) does not hold, and $\lambda_B c_A \geqslant \lambda_A c_B$. Otherwise, the acquisition occurs solely to prevent espionage rather than to also improve the development technology.

Figure 3 shows a numerical example illustrating a case where B's development technology is inferior to A's. For $\pi < 0.4$, firm A pays a positive price to acquire B with the sole purpose of preventing espionage. For $\pi > 0.4$, firm A acquires B both to prevent espionage and to improve its development technology.

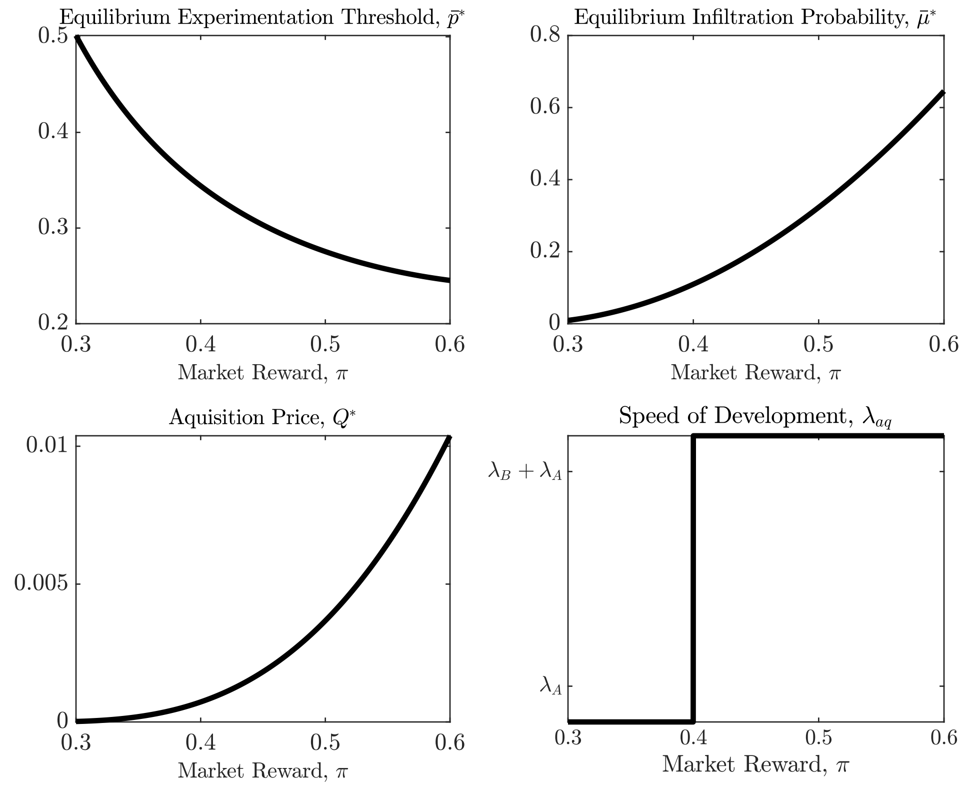

Figure 3: Infiltration probability and decision to acquire firm B as a function of the market reward, π. Model parameters: $k = 0.1$; $\eta = 2$; $p_0 = 0.75$; $r = 1$; $\lambda_A = 1$; $\lambda_B = 0.8$; $c_A = 0.1$; $c_B = 0.2$; $c(\mu) = 0.04\mu^{1.5}$.

6 Third-party Espionage

In this section, we assume that firm B cannot spy. Instead, there is a hacker out there who can. In particular, a hacker chooses how much effort to put into infiltrating firm A at time 0, and his espionage cost is the same as firm B's in the baseline case.

The main difference with the baseline model is that the hacker has two potential buyers. We assume there is perfect commitment on the side of the hacker: If he trades with firm A, he commits not to trade with firm B and viceversa. Furthermore, the hacker does not trade the breakthrough with firm A (A knows what it knows). Instead, the hacker makes firm A aware of its "vulnerability," and uses the stolen breakthrough as proof. Once firm A is made aware of its vulnerability, it immediately fixes it.

The first question we ask is: who does the hacker want to trade with in case of successfully breaching firm A? The hacker can and will trade immediately after a breakthrough occurs.

Firm B's payoff from buying the breakthrough from the hacker is V_B^C, while firm A's is $V_A^L - V_A^C$ (see Proposition 1). The hacker trades with the firm with the highest willingness to pay, receiving a payment equal to the other firm's willingness to pay (i.e., a second-price auction). Under these assumptions, we have two cases: (1) If $V_B^C > V_A^L - V_A^C$ firm B buys from the hacker at a price $Q_H = V_A^L - V_A^C$; and (2) If $V_B^C \leqslant V_A^L - V_A^C$ firm A buys from the hacker at a price $Q_H = V_B^C$.

Case 1. The hacker trades with firm B. In this case, the hacker receives a payoff of $Q_H = V_A^L - V_A^C < V_B^C$ from successfully infiltrating firm A, conditional on a breakthrough. Thus, when the hacker chooses his espionage effort, he solves a problem analogous to (6), where instead of $W_B(\bar{p})$ the payoff is now $W_H(\bar{p})$ with:

$$W_B(\bar{p}) = p_0 Q_H \frac{\eta}{\eta + r}\left(1 - \left(\frac{1-p_0}{p_0}\right)^{\frac{\eta+r}{\eta}}\left(\frac{1-\bar{p}}{\bar{p}}\right)^{-\frac{\eta+r}{\eta}}\right). \tag{11}$$

Note that, since we are in the case $Q_H < V_B^C$, then the hacker optimal espionage is always less than the espionage effort of firm B in the baseline case. That is, the hacker will exert *less* espionage effort than a rival firm, so firm A will experiment longer. In other words, an independent hacker is preferred to a rival vertically-integrated with a hacker.

Lastly, if firm A knew the identity of the hacker and could contract him at time zero it will always do so. The analysis is analogous to that in section 5.

Case 2. The hacker trades with firm A. In this case, firm A knows it would acquire the information at the breakthrough and would have to pay $Q_H = V_B^C$. Thus, all-else-equal, the hacker's espionage effort is the same as firm B in the baseline case (see (11) and (5)).

Firm A's continuation payoff after a breakthrough, conditional on an espionage effort μ by the hacker, is:

$$\begin{aligned} V_{A,H}(\mu) &= \mu(V_A^L - V_B^C) + (1-\mu)V_A^L, \\ &= V_A^L - \mu V_B^C. \end{aligned}$$

That is, firm A gets the continuation payoff of developing alone, except in the case of successful infiltration, in which case pays the hacker V_B^C. Given that in this case $V_B^C \leqslant V_A^L - V_A^C$, we have:

$$V_{A,H} \geqslant (1-\mu)V_A^L + \mu V_A^C = V_A(\mu).$$

In other words, firm A's continuation value is higher when it trades with the hacker than in the baseline case. Thus, fixing μ, firm A experiments longer relative to the baseline case.

It is easy to understand the equilibrium effect from Figure 1. The hacker's best response is identical to firm's best response in the baseline case. However, firm A's best response shifts down, pointwise (i.e., the experimentation threshold $\bar{p}(\cdot)$ decreases pointwise). Therefore, in equilibrium, there will be more espionage and more experimentation.

These results together imply the following proposition.

Proposition 9. *There is more experimentation when espionage is carried out by an independent hacker rather than a competitor.*

7 Extensions

7.1 Endogenous Timing of a Break-In

In this extension, we consider an alternative method of industrial espionage. Rather than "planting a bug" like in the baseline model, we now study the case of a one-time break-in.

Recall that in the baseline model firm B chooses to infiltrate firm A with probability μ at time zero. Conditional on a successful infiltration, firm B observes firm A's information in real-time until the end of the game. Instead, in this section, we explore espionage dynamics when firm B chooses the *timing* of a one-time break into firm A, which allows B to observe A's information *only* at that particular point in time. As in the baseline case, we assume that firm A cannot detect the breach.

If the break-in occurs before the arrival of firm A's breakthrough, then firm B gains nothing because there is no secret to steal. If it happens after the breakthrough but before firm A's development, then firm B steals the new technology and immediately starts developing the product. If the break-in happens after firm A completed the product, then firm B gains nothing from breaking in.

To solve this completely dynamic model, we make several simplifying assumptions, to obtain a tractable analytical solution. First, firm B's development is instantaneous, i.e., $\lambda_B = \infty$. Thus, when firm A is in the development stage, it has complete information about whether firm B has stolen the technology because a successful break-in immediately ends the game.

Second, development stage is cheap, i.e., $c_A = c_B = 0$. Third, the cost of breaking in is normalized to zero, and firm B never fails to break-in (in contrast to the baseline model where it succeeds with probability μ).

Proposition 10. *Let $\lambda_B = \infty$, $c_A = c_B = 0$. When firm B chooses the timing of costless and certainly successful one-time break in, the equilibrium involves randomization of break-in times in the interval $\mathcal{B} = [\underline{t}, \bar{t}]$. When $t < \underline{t}$, firm A experiments using all its resources (i.e., $x_t = 1$). When $t \in \mathcal{B}$, firm A uses some resources to experiments (i.e., $x_t < 1$). When $t > \bar{t}$, firm A again experiments using all of its resources.*

Proof. Fixing firm B's strategy, let $V_A^S(\tau, s)$ be firm A's expected payoff evaluated at time s when the breakthrough occurs at $\tau \leqslant s$, conditional on no break-in between τ and s. Firm B's break-in time is a random variable distributed according to $F(\cdot)$, which for now we assume continuous with support on $[\underline{t}, \bar{t}]$. The Hamilton-Jacobi-Bellman equation reads:

$$rV_A^S(\tau, s) = \lambda_A(\pi - V_A^S(\tau, s)) + \frac{F'(s)}{1 - F(s) + F(\tau)}(0 - V_A^S(\tau, s)) + \frac{\partial V_A^S(\tau, s)}{\partial s}, \tag{12}$$

At $s = \bar{t}$, firm A no longer faces a break in threat, and hence $V_A^S(\tau, \bar{t}) = \frac{\lambda_A \pi}{\lambda_A + r}$. The ODE (12) with this boundary condition admits the following solution:

$$V_A^S(\tau, s) = \frac{e^{-(\lambda_A + r)(\bar{t} - s)}\lambda_A \pi F(\tau)}{(\lambda_A + r)(1 + F(\tau) - F(s))} + \frac{\int_s^{\bar{t}} e^{-(\lambda_A + r)(s' - s)}\lambda_A \pi(1 + F(\tau) - F(s'))\mathrm{d}s'}{1 + F(\tau) - F(s)}. \tag{13}$$

At time zero, firm A chooses the experimentation effort at each instant, $x_s \in [0, 1]$, to maximize:

$$U_A = \max_{x_s \in [0,1]} \int_0^\infty x_\tau(\eta p_\tau V_A^S(\tau, \tau) - k)e^{-\int_0^\tau \eta x_s p_s \mathrm{d}s} e^{-r\tau}\mathrm{d}\tau. \tag{14}$$

By Bayes' rule, $\dot{p}_s = -\eta x_s p_s(1 - p_s)$. With the change of variables $\ell_s \equiv \log \frac{1 - p_s}{p_s}$, we have $\dot{\ell}_s = \eta x_s$. Therefore, (14) can be rewritten as:

$$U_A = \max_{x_s \in [0,1], \ell_s} \frac{1}{r\eta} \int_0^\infty e^{-rs}\left(-kr\ell_s + (1 + e^{-\ell_s})(kr - \eta r V_A^S(s, s) + \eta \frac{\mathrm{d}}{\mathrm{d}s} V_A^S(s, s))\right)\mathrm{d}s,$$

such that $\ell_0 = \log \frac{1 - p_0}{p_0}$ and $\dot{\ell}_s = \eta x_s$. Whenever x_s is interior, ℓ_s must point-wise maximize the expression inside the integral above, so:

$$\ell_s = \log\left(\frac{\eta}{kr}\left(rV_A^S(s, s) - \frac{\mathrm{d}}{\mathrm{d}s}V_A^S(s, s)\right) - 1\right). \tag{15}$$

Firm B, on the other hand, is indifferent among all break-in times that maximize its payoff. If the planned breach occurs at time t, the unconditional probability that firm A has discovered the technology but has not yet developed the product is

$$\int_0^t e^{-\lambda_A(t-s)-\eta X_s}\eta x_s \mathrm{d}s,$$

where $X_s \equiv \int_0^s x_{s'}\mathrm{d}s'$ is the cumulative research effort. Hence, firm B's expected payoff from choosing an optimal break-in time is:

$$U_B = \max_{t\geqslant 0} \pi e^{-rt}\int_0^t e^{-\lambda_A(t-s)-\eta X_s}\eta x_s \mathrm{d}s.$$

On the support $[\underline{t}, \bar{t}]$, the objective must be constant in t and equal to U_B. Solving this integral equation in t, we have:

$$X_t = -\frac{1}{\eta}\log\left(e^{-\eta\underline{t}} + \frac{U_B(\lambda_A + r)}{\pi r}(e^{-r\underline{t}} - e^{-rt})\right). \tag{16}$$

For $s < \underline{t}$, conjecture that $x_s = 1$ such that $X_s = s$. Then the integral equation also requires:

$$U_B e^{(\lambda_A + r)\underline{t}} = \frac{(e^{(\lambda_A-\eta)\underline{t}} - 1)\eta\pi}{\lambda_A - \eta}. \tag{17}$$

Plugging (13) into (15) and relating (16) by $\ell_s = \ell_0 + \eta X_s$, we have an integral equation for $F(\cdot)$. Reducing it to a second order ODE, we have an analytical solution for F with two constants c_1 and c_2. The integral equation is one condition (Condition 1).

Next, we require $F(\underline{t}) = 0$ (Condition 2) and $F(\bar{t}) = 1$ (Condition 3). Also, we already have (17) as (Condition 4) and $x_{\bar{t}} = 1$ as (Condition 5). Therefore, we have five conditions and five unknowns ($\underline{t}$, $\bar{t}$, c_1, c_2, U_B). A numerical solution is available. □

With parameters $\eta = 1$, $\lambda_A = 2$, $r = 1$, $\pi = 1$, $k = 0.1$ and $p_0 = \frac{1}{1+e^{1/2}}$, we have $\underline{t} = 0.07$ and $\bar{t} = 1.16$. Before $\underline{t}$, firm A researches at full speed, and firm B does not break in. Between $\underline{t}$ and $\bar{t}$, firm A researches at interior speed and firm B randomizes breaking in. After $\bar{t}$, firm A researches at full speed again, and firm B does not break in anymore. Because of the last stage, the eventual amount of learning is not affected by the presence of firm B, but the learning is delayed.

7.2 Detecting and Punishing Espionage

While our baseline model assumes that espionage is undetectable, we can extend our results to allow for the possibility of detecting espionage before experimentation has begun. The timing is: (1) Firm B attempts to infiltrate firm A at time 0. (2) With probability q, at time 0, firm A detects an infiltration, if one has occurred, in which case firm B pays a penalty D.

Under those assumptions, firm B's expected payoff, for a given experimentation threshold by firm A, is now

$$(1-q)\mu W_B(\bar{p}^*) - c(\mu) - qD\mu.$$

Note firm B's choice of μ is equivalent to the choice of μ in the baseline model with a modified cost function

$$\hat{c}(\mu) = \frac{c(\mu) + qD\mu}{1-q}.$$

If firm A detects infiltration, then it will experiment until the belief falls to the optimal single-agent threshold. If firm A does not detect the infiltration, however, then its posterior belief that B has successfully infiltrated is

$$\hat{\mu}(\mu) = \frac{(1-q)\mu}{(1-q)\mu + 1 - \mu}.$$

Note that $\hat{\mu}(\cdot)$ is strictly increasing.

Then, to find an equilibrium, we fixed $\bar{p}(\mu) = \frac{k}{\eta \hat{V}_A(\mu)}$, where $\hat{V}_A = V_A(\hat{\mu}(\mu))$, strictly increasing in μ.

Since the proof of equilibrium existence only relies on the monotonicity properties of $\bar{p}(\mu)$ and $\mu(\bar{p})$, an equilibrium in this extended setting will exists.

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9 Appendix: Proofs

Proof of Proposition 1

Proof. By assumption, firms will develop the product until one of them is successful.[11] Then, the Bellman equation for the value to firm $i = A, B$ of working under competition is:

$$rV_i^C = -c_i + \lambda_i(\pi - V_i^C) + \lambda_j(0 - V_i^C).$$

Solving for V_i^C from the above, we get:

$$V_i^C = \frac{\lambda_i \pi - c_i}{r + \lambda_i + \lambda_j}.$$

The value of firm A from working alone at time t can be found by setting $\lambda_B = 0$ in the expression above, so:

$$V_A^L = \frac{\lambda_A \pi - c_A}{r + \lambda_A}.$$

□

Proof of Proposition 2

Proof. To solve the Hamilton-Jacobi-Bellman equation:

$$rW_A(p) = \max_{x \in [0,1]} \left[-k + \eta p(V_A(\mu) - W_A(p)) - \eta p(1-p)W_A'(p)\right] x,$$

let $B = -k + \eta p(V_A(\mu) - W_A(p)) - \eta p(1-p)W_A'(p)$. Optimization requires $x = 1$ if $B > 0$, $x = 0$ if $B < 0$ and $x \in [0,1]$ if $B = 0$. It can be shown that there exists a unique cutoff belief $p^* > 0$ such that $x = 1$ for $p > p^*$ and $x = 0$ for $p < p^*$. In other words, the firm experiments if and only if the belief is sufficiently large. When the firm stop experimenting, for any $p < p^*$, $W_A(p) = 0$. Evaluating B at p^* and imposing value matching and smooth

[11] This assumption means that the development's flow cost is not too large.

pasting conditions we get

$$p^* = \frac{k}{\eta V_A(\mu)}.$$

□

Proof of Equation 5

Proof. Let $W_B(p)$ be firm B's value function if it successfully infiltrates and firm A's belief is p. Note that, by infiltrating, firm B learns all the information that firm A knows, so firm A's belief is not private. If $p < p^*$, then firm A gives up experimentation, and firm B gets zero, so $W_B(p) = 0$. If $p > p^*$, in equilibrium firm A chooses $x = 1$ and therefore:

$$rW_B(p) = \eta p(V_B^C - W_B(p)) - \eta p(1-p)W_B'(p).$$

Coupled with the boundary condition $W_B(p^*) = 0$, firm B's value function is what is shown in the proposition. □

Proof of Proposition 6

Proof. To compute the comparative static of the equilibrium value $\bar{p}^*$ with respect to π, we write $\bar{p}^*$ as the solution of the fixed point equation:

$$\bar{p}^* = \bar{p}(\pi, \mu(\pi, \bar{p}^*)).$$

Differentiating with respect to π we get:

$$\frac{\mathrm{d}\bar{p}^*}{\mathrm{d}\pi} = \frac{\partial \bar{p}(\pi, \mu(\pi, \bar{p}^*))}{\partial \pi} + \frac{\partial \bar{p}(\pi, \mu(\pi, \bar{p}^*))}{\partial \mu}\left[\frac{\partial \mu(\pi, \bar{p}^*)}{\partial \pi} + \frac{\partial \mu(\pi, \bar{p}^*)}{\partial \bar{p}}\frac{\mathrm{d}\bar{p}^*}{\mathrm{d}\pi}\right]$$

Simplifying:

$$\frac{\mathrm{d}\bar{p}^*}{\mathrm{d}\pi}\left[1 - \frac{\partial \bar{p}(\pi, \mu(\pi, \bar{p}^*))}{\partial \mu}\frac{\partial \mu(\pi, \bar{p}^*)}{\partial \bar{p}}\right] = \frac{\partial \bar{p}(\pi, \mu(\pi, \bar{p}^*))}{\partial \pi} + \frac{\partial \bar{p}(\pi, \mu(\pi, \bar{p}^*))}{\partial \mu}\frac{\partial \mu(\pi, \bar{p}^*)}{\partial \pi}. \tag{18}$$

Note that:

$$\frac{\partial \bar{p}(\pi, \mu(\pi, \bar{p}^*))}{\partial \pi} = \frac{-k}{\eta}\left(\frac{1}{V_A(\mu)}\right)^2 \frac{\partial V_A(\mu)}{\partial \pi} < 0 \text{ and } \frac{\partial \bar{p}(\pi, \mu(\pi, \bar{p}^*))}{\partial \mu} = \frac{-k}{\eta}\left(\frac{1}{V_A(\mu)}\right)^2 \frac{\partial V_A(\mu)}{\partial \mu} > 0,$$

because

$$\frac{\partial V_A(\mu)}{\partial \pi} = \left(\mu\frac{\lambda_A}{\lambda_A+\lambda_B+r} + (1-\mu)\frac{\lambda_A}{\lambda_A+r}\right) > 0 \text{ and } \frac{\partial V_A(\mu)}{\partial \mu} = V_A^C - V_A^L < 0.$$

The bracket multiplying $\frac{\mathrm{d}\bar{p}^*}{\mathrm{d}\pi}$ in (18) is positive because $\frac{\partial \mu(\pi,\bar{p})}{\partial \bar{p}} < 0 < \frac{\partial \bar{p}(\pi,\mu)}{\partial \mu}$ and, therefore, the sign of $\frac{\mathrm{d}\bar{p}^*}{\mathrm{d}\pi}$ is the same as the sign of the right-hand side of (18).

In equilibrium we have $\mu(\pi,\bar{p}^*) = [c']^{-1}(W_B(\bar{p}^*))$. Then:

$$\frac{\partial \mu(\pi,\bar{p}^*)}{\partial \pi} = ([c']^{-1})'(W_B(\bar{p}^*))\frac{\partial W_B(\bar{p}^*)}{\partial V_B^C}\frac{\partial V_B^C}{\partial \pi}.$$

We have $\frac{\partial W_B(\bar{p}^*)}{\partial V_B^C} = \frac{W_B(\bar{p}^*)}{V_B^C}$ and $\frac{\partial V_B^C}{\partial \pi} = \frac{\lambda_B}{\lambda_B+r}$. Then:

$$\frac{\partial \mu(\pi,\bar{p}^*)}{\partial \pi} = ([c']^{-1})'(W_B(\bar{p}^*))\frac{W_B(\bar{p}^*)}{V_B^C}\frac{\lambda_B}{\lambda_B+r}.$$

Therefore:

$$\text{sign}\left[\frac{\mathrm{d}\bar{p}^*}{\mathrm{d}\pi}\right] = \text{sign}\left[\underbrace{\frac{\partial \bar{p}(\pi,\mu(\pi,\bar{p}^*))}{\partial \pi}}_{<0} + \underbrace{\frac{\partial \bar{p}(\pi,\mu^*(\pi,\bar{p}^*))}{\partial \mu}}_{>0}\underbrace{\frac{\partial \mu(\pi,\bar{p}^*)}{\partial \pi}}_{>0}\right]$$

The bracket above is negative when:

$$\frac{-k}{\eta}\left(\frac{1}{V_A(\mu)}\right)^2\left[\frac{\partial V_A(\mu)}{\partial \pi} + \frac{\partial V_A(\mu)}{\partial \mu}([c']^{-1})'(W_B(\bar{p}^*))\frac{W_B(\bar{p}^*)}{V_B^C}\frac{\lambda_B}{\lambda_B+r}\right] < 0,$$

which is equivalent to:

$$\frac{\partial V_A(\mu)}{\partial \pi} > -\frac{\partial V_A(\mu)}{\partial \mu}([c']^{-1})'(W_B(\bar{p}^*))\frac{W_B(\bar{p}^*)}{V_B^C}.$$

Using that $\frac{-\partial V_A(\mu)}{\partial \mu} = V_A^L - V_A^C$ we get:

$$\frac{\partial V_A(\mu)}{\partial \pi} > ([c']^{-1})'(W_B(\bar{p}^*))\frac{W_B(\bar{p}^*)}{V_B^C}(V_A^L - V_A^C).$$

Next, note that $\mu^* = \mu(\pi, \bar{p}^*)$. Differentiating with respect to π we get:

$$\frac{\mathrm{d}\mu^*}{\mathrm{d}\pi} = \frac{\partial \mu(\pi, \bar{p}^*)}{\partial \pi} + \frac{\partial \mu(\pi, \bar{p}^*)}{\partial \bar{p}} \frac{\mathrm{d}\bar{p}^*}{\mathrm{d}\pi}.$$

Replacing $\frac{\mathrm{d}\bar{p}^*}{\mathrm{d}\pi}$ from (18) and simplifying we get:

$$\frac{\mathrm{d}\mu^*}{\mathrm{d}\pi} = \frac{\frac{\partial \mu(\pi,\bar{p}^*)}{\partial \pi} + \frac{\partial \mu(\pi,\bar{p}^*)}{\partial \bar{p}} \frac{\partial p(\pi,\mu^*)}{\partial \pi}}{1 - \frac{\partial \bar{p}(\pi,\mu(\pi,\bar{p}^*))}{\partial \mu} \frac{\partial \mu(\pi,\bar{p}^*)}{\partial \bar{p}}},$$

which is positive because both the numerator and the denominator are positive. ☐

Proof of Proposition 7

Proof. **Increasing λ_B.** Similar to the proof of Proposition 6, to compute the comparative static of the equilibrium value $\bar{p}^*$ with respect to λ_B, we write $\bar{p}^*$ as the solution of the fixed point equation:

$$\bar{p}^* = \bar{p}(\lambda_B, \mu(\lambda_B, \bar{p}^*)).$$

Differentiating with respect to λ_B we get:

$$\frac{\mathrm{d}\bar{p}^*}{\mathrm{d}\lambda_B} \left[1 - \frac{\partial \bar{p}(\lambda_B, \mu(\lambda_B, \bar{p}^*))}{\partial \mu} \frac{\partial \mu(\lambda_B, \bar{p}^*)}{\partial \bar{p}}\right] = \frac{\partial \bar{p}(\pi, \mu(\pi, \bar{p}^*))}{\partial \lambda_B} + \frac{\partial \bar{p}(\pi, \mu(\pi, \bar{p}^*))}{\partial \mu} \frac{\partial \mu(\pi, \bar{p}^*)}{\partial \lambda_B}. \quad (19)$$

It is easy to see that $\frac{\partial \mu(\lambda_B,\bar{p})}{\partial \lambda_B} > 0$ and $\frac{\partial \bar{p}(\lambda_B,\mu)}{\partial \lambda_B} > 0$, so the right-hand side of the equation above is positive. The bracket in the left-hand side is also positive. Therefore, $\frac{\mathrm{d}\bar{p}^*}{\mathrm{d}\lambda_B} > 0$. To see that the impact of increasing λ_B on μ^* is ambiguous, note that:

$$\bar{\mu}^* = \mu(\lambda_B, \bar{p}(\lambda_B, \mu^*)).$$

Differentiating with respect to λ_B, and doing some simplifications we get:

$$\operatorname{sign} \frac{\mathrm{d}\mu^*}{\mathrm{d}\lambda_B} = \operatorname{sign} \left[\frac{\partial \mu(\pi, \bar{p}^*)}{\partial \lambda_B} + \frac{\partial \mu(\pi, \bar{p}^*)}{\partial \bar{p}} \frac{\partial \bar{p}(\lambda_B, \mu^*)}{\partial \lambda_B}\right].$$

The term in the brackets is positive when:

$$\frac{\partial \mu(\pi, \bar{p}^*)}{\partial \lambda_B} > \frac{-\partial \mu(\pi, \bar{p}^*)}{\partial \bar{p}} \frac{\partial \bar{p}(\lambda_B, \mu^*)}{\partial \lambda_B}.$$

Increasing λ_A. Analogous to the previous proof, we write

$$\bar{p}^* = \bar{p}(\lambda_A, \mu(\lambda_A, \bar{p}^*)).$$

Differentiating with respect to λ_A we get,

$$\frac{\mathrm{d}\bar{p}^*}{\mathrm{d}\lambda_A}\left[1 - \frac{\partial \bar{p}(\lambda_A, \mu(\lambda_B, \bar{p}^*))}{\partial \mu}\frac{\partial \mu(\lambda_A, \bar{p}^*)}{\partial \bar{p}}\right] = \frac{\partial \bar{p}(\pi, \mu(\pi, \bar{p}^*))}{\partial \lambda_A} + \frac{\partial \bar{p}(\pi, \mu(\pi, \bar{p}^*))}{\partial \mu}\frac{\partial \mu(\pi, \bar{p}^*)}{\partial \lambda_A}. \quad (20)$$

It is easy to see that $\frac{\partial \mu(\lambda_B, \bar{p})}{\partial \lambda_A} < 0$ and $\frac{\partial \bar{p}(\lambda_B, \mu)}{\partial \lambda_B} < 0$, so the right-hand side of the equation above is negative. The bracket in the left-hand side is also positive. Therefore, $\frac{\mathrm{d}\bar{p}^*}{\mathrm{d}\lambda_B} < 0$. To see that the impact of increasing λ_A on μ^* is ambiguous, note that

$$\bar{\mu}^* = \mu(\lambda_A, \bar{p}(\lambda_A, \mu^*)).$$

Differentiating with respect to λ_A, and doing some simplifications we get

$$\text{sign}\frac{\mathrm{d}\mu^*}{\mathrm{d}\lambda_A} = \text{sign}\left[\frac{\partial \mu(\pi, \bar{p}^*)}{\partial \lambda_A} + \frac{\partial \mu(\pi, \bar{p}^*)}{\partial \bar{p}}\frac{\partial \bar{p}(\lambda_A, \mu^*)}{\partial \lambda_A}\right]$$

The term in the brackets is positive when

$$\frac{\partial \mu(\pi, \bar{p}^*)}{\partial \lambda_A} > \frac{-\partial \mu(\pi, \bar{p}^*)}{\partial \bar{p}}\frac{\partial \bar{p}(\lambda_A, \mu^*)}{\partial \lambda_A}$$

Decreasing η. We make the following change of variables: $\gamma = \frac{\eta + r}{\eta}$ and $Q_0 = \frac{1-p_0}{p_0}$. Then, $W_B(\bar{p})$ can be written as:

$$\widehat{W}_B(\gamma, \bar{p}) = \frac{V_B^C}{\gamma(1+Q_0)}\left[1 - \left(\frac{Q_0\bar{p}}{1-\bar{p}}\right)^{\gamma}\right].$$

Taking partial derivative we get

$$\frac{\partial \widehat{W}_B(\gamma, \bar{p})}{\partial \gamma} = \frac{-\widehat{W}_B(\gamma, \bar{p})}{\gamma} - \frac{V_B^C}{\gamma(1+Q_0)}\left(\frac{Q_0\bar{p}}{1-\bar{p}}\right)^{\gamma}\ln\left(\frac{Q_0\bar{p}}{1-\bar{p}}\right).$$

Given that $Q_0 < \frac{1-\bar{p}}{\bar{p}}$ the second term in the expression above is positive. Thus, $\widehat{W}$ can increase or decrease when η decreases and, consequently, $\mu(\eta, \bar{p})$ can increase of decrease when η increases.

On the other hand, $\frac{\partial \bar{p}(\eta, \mu)}{\partial \eta} = \frac{-\bar{p}}{\eta} < 0$, so $\bar{p}(\eta, \cdot)$ decreases pointwise when η increases.

This shows that the comparative statics, both for p^* and μ^* are ambiguous when η decreases.

Increasing k. When experimentation is more costly, firm A has less incentives to experiment and therefore $\bar{p}(\cdot)$ increases pointwise. For a fixed μ, the threshold belief to stop experimentation increases. There is no direct effect of k on firm B: firm B's best response function is unaffected by k. Directly from Figure 1 we can see that in equilibrium B is less willing to infiltrate because firm A experiment less.

□

9.1 Proof of Proposition 8

Proof. Using development technology k is better than using both when:

$$\frac{\lambda_k \pi - c_k}{\lambda_k + r} < \frac{(\lambda_A + \lambda_B)\pi - c_A - c_B}{\lambda_A + \lambda_B + r},$$

or equivalently:

$$(\lambda_k \pi - c_k)(\lambda_A + r) + (\lambda_k \pi - c_k)\lambda_B < (\lambda_k + r)(\lambda_A \pi - c_A + \lambda_B \pi - c_B),$$

which reduces to:

$$r\pi > \left(\frac{\lambda_k + r}{\lambda_{-k}}\right) c_{-k} - c_k. \tag{21}$$

If the firm uses a single development technology, then A is preferred to be when:

$$\frac{\lambda_A \pi - c_A}{\lambda_A + r} \geqslant \frac{\lambda_B \pi - c_B}{\lambda_B + r},$$

which is equivalent to $\pi r(\lambda_A - \lambda_B) \geqslant (\lambda_B + r)c_A - (\lambda_A + r)c_B$.

□