Finance and Schumpterian Rents: On the Timing of Innovation

Chris Yung*

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Abstract

I model an innovation game in which firms can choose to be leaders or followers. Internal finance leads to a stalemate in which each firm wants to free-ride on the others' experimentation costs. Therefore, no innovation occurs. When instead firms compete in the capital markets to finance innovation, there is an endogenous cost to delay. Waiting to make risky irreversible investment conveys more pessimist information to suppliers of finance and therefore depresses security prices. I characterize the relative sizes of waves of leaders and followers in innovation cycles − and the endogenous, intertemporal distribution of quality as each wave builds and crashes − as a function of the risk of the innovation and the amount of external finance required.

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*Associate Professor of Commerce, McIntire School of Commerce, University of Virginia. I would like to thank Roberto Pinheiro...

1 Introduction

Schumpeter (1912) characterizes innovation as occuring in discrete bursts of "creative destruction." In particular, the manner is which business is conducted has periods of relative stability, only to be episodically disrupted by innovators − Unternehmergeist, as Schumpeter called them, or "wild spirits" − who conjure up new, creative ways to combine existing resources. These novel combinations threaten the status quo and rapidly advance social welfare as businesses adjust to the new paradigms.

In the above story, the incentives to innovate are left essentially unmodeled. This may be without loss of generality in some cases. For example, if someone happens upon a brilliant commercial idea by sheer luck, he may need little incentive to get the idea financed and implemented.[1]

In other cases, however, innovation requires costly and time-consuming experimentation. Is it unclear in these cases that rational individuals have much incentive to bear these costs. Suppose, for example, that experimental outcomes are publicly observable with relatively short lags. Why would anyone bear these costs, if one can instead simply mimic the results of successful pioneers? Without a solution to this problem, no innovation can occur.

The standard solution to this stalemate is to consider innovators with market power, arising either naturally (e.g., monopoly firms) or by legal construction (e.g., patents).[2] Given a successful innovation, market power

[1]Keynes (1960) likewise offers that this process depends upon "a sufficient supply of individuals of sanguine temperament and constructive impulses." Again the driving force is Unternehmergeist mixed with a dose of luck.

[2]See Loury (1979) and Lee and Wilde (1980) for canonical analyses. Applications include the effect of patents and licensing in a duopoly (Katz and Shapiro, 1985), adoption and imitation as a function of evolving public information about the profitability of the innovation (Jensen, 1982), oligopoly power and the rate of obsolesce of existing technology (Gifford, 1992), optimal regulation of an innovating monopolist (Lewis and Yildirim,

enables the pioneer to capture temporary abnormal profits, or *Schumpterian rents*, which erode over time as the technology of their competitors catches up.

In this note I demonstrate that external financing also generates an endogenous benefit to being a pioneer in the innovation game. In effect, external financing creates a type of Schumpterian rent which is quite distinct from those that exist on the product market side. Consequently, *reliance on external finance leads agents to innovate more rapidly than had they used internal finance.*

Two assumptions drive the results. First, agents are heterogeneous. Payoffs to taking the innovative action are risky, having both a public component (observable and common to all agents) and a private, agent-specific component. This heterogeneity ensures that agents have differential incentive to innovate. Second, I allow that agents may not be able to fully self-finance the research costs. If not, they must obtain external financing, implying that payoffs are shared by the agent and the financier.

These two assumptions interact. Convincing others to supply funds requires convincing them that one's quality is of an acceptable level. As I show, waiting too long to attempt the innovation reveals low quality, and thus there is an endogenous cost to delay. In particular, for a given set of public information, agents obtain better financing terms from innovating early. The tradeoff is that one obtains more accurate public information about by waiting. In effect, hesitation enables agents to "wait out" risk using the information generated by the leaders. Yet the benefit of this delay depends on the agent's quality. The projects of very high quality agents are

2002), "natural" lags in imitation (Benoit, 1985), and optimal allocation of property rights between researchers, financiers and customers (Aghion and Tirole, 1994) when the relevant friction is researchers' costly effort. See Kamien and Schwarz (1975) for an excellent review of the earlier literature.

valuable under a broader range of information. Hence, information resolution is less critical for them, enabling them to innovate earlier. Thus, in equilibrium, high-quality agents innovate before low-quality agents. In turn, because early financing is associated with attractive security pricing, the adverse selection problem creates a rush among entrepreneurs to innovate first. Thus, we obtain endogenous clustering in which (sometimes large) numbers of agents act simultaneously and before they would have in a first-best world.

The model exhibits a version of Schumpeter's waves, i.e., innovation followed rapidly by imitation. The comparative static results regarding risk have fairly intuitive properties. Suppose the research project is relatively low risk. Then, by definition, the actions of pioneers do not add much information. In that case, firms have relatively little reason to wait for resolution uncertainty, and the majority of firms will choose to enter the market early. Thus, the amount of (early) innovation varies inversely with the risk therein.

The model also illustrates more subtle indirect effects. For example, consider the case described above when many agents rush to enter initial wave. As the initial firms of the highest quality, a large exodus in the first wave implies that firms remaining in the pool are of relatively low quality. Suppliers of finance are aware of this effect and thus pricing becomes worse for firms opting to enter the second wave. In turn, this reduces demand in the second wave. The overall effect of a large first wave therefore is to cause the second wave to be relatively small, and of low quality. Note this effect persists even though the risk has been resolved by the time second-wave entrants make their choice.

1.1 Related Literature

Of the papers cited in footnote 2, perhaps the closest related is Jensen (1982) in which firms make an irreversible decision to adopt a risky new technology.[3] Though the technology is common to all firms, they have different prior beliefs about the payoffs. This decision is modeled as an optimal stopping problem with public information about the payoffs evolving over time, and agents dynamical updating their beliefs via Bayes rule. This model setup is therefore quite similar to the current one. In equilibrium Jensen (1982) obtains an (empirically familiar) S-shaped adoption pattern in which a few pioneers are followed by increasingly rapid imitation, which then tapers off as beliefs converge.

Several features of Jensen's model are echoed here. Yet the cost of delay in Jensen's model is one of pure time value of money, i.e., if the new technology is profitable, one would like to adopt it as early as possible. By contrast, the economic cost in the current model is that delay conveys unfavorable news to outside investors. Consequently internal and external finance have differential impacts on innovation, in particular on the relative size and timing of the waves that occur in equilibrium. Given the amount of innovation that is financed externally, this distinction appears to be empirically relevant.

The role of security issuance waves and their connection to issue prices has also been considered in a growing finance literature on intial public offerings (reviewed in Table 1). A focus in many of these models has been on IPO "underpricing" – defined as the discount that issuers give investors to compensate them for either 1) de novo information production as in Chemmanur (1993) or 2), the winners curse due to asymmetric information across investors as in Rock (1986). These models typically lack either endogenous timing or private information of the selling shareholders, and therefore capture a different set of intuition than developed here.

[3] Aghion and Griffith (2005) review another branch of IO literature based on linear or circular cities. Innovation in that context is defined as firm entry. This notion of innovation is quite different from the one employed here in which an agent performs experiments on a project with uncertain prospects, and the critical decision is whether to do so *before* other agents.

2 The Model

Projects have gross returns $\tilde{X} = iZ$. The random variable i takes values $i \in \{0, 1\}$ where the probability $\pi_i = Pr\{i = 1\}$ is private information. These success probabilities are uniformly distributed along the interval $[i_{MIN}, i_{MAX}]$. The multiplicative factor $Z \in \mathbb{R}$ is common to all firms. Information arrives about this public variable over time in a process which is described in more detail below. Innovators have capital V to contribute to the project; however, the project also requires another capital contribution of K which must be raised externally.

The proposed equilibrium is of the following form. Agents issue securities in (up to possibly) k different waves. The first wave consists of all agents on the interval $[i_1, i_{MAX}]$ where the value i_1 is endogenously determined. After this wave is completed, news is revealed about Z. Indeed, it may be useful to view the signal Z as being generated by the wave itself. For example, a wave of IPOs may stimulate information production among investors in the primary and secondary markets. As an important side effect of this price discovery process, agents that have not yet entered the market are able to extract value-relevant information and tailor their entry/exit decision accordingly.

Sufficiently favorable news regarding Z may then trigger a second wave. The subset of followers will be denoted $[i_2, i_1]$ for some $i_2 < i_1$ where i_2 is again determined endogenously. The key feature of the model is that wave 2 commences only if news about Z revealed in wave 1 was better than expected. Otherwise, issuers in the interval $[i_2, i_1]$ would have had strictly stronger incentive to enter wave 1. By doing so, they would have obtained better pricing since 1) the market would have imputed higher quality to them, and 2) news about Z was at that time more favorable.

As will be shown, these waves can then continue for as long as news about

Z continues to be better than expected. For example, in the context of Z being summarized by a coin flip (where heads indicates a first-order stochastic improvement to all firms) waves will continue for as long as the coin continues to generate heads. Upon the first occurence of tails, waves discontinue.[4] Thus, waves in this model always build up and then subsequently crash. In particular, there is overinvestment with probably one: entrants in the final wave find their projects to be negative net present value conditional on the terminating coin flip (tails).

2.1 Information about $\tilde{Z}$

Assume that Z is gradually revealed by a succession of coin flips. Each successive coin flip reveals information about Z as follows.

$$Pr(Heads\ on\ flip\ j \mid Z = 0) = e_1^j$$

$$Pr(Heads\ on\ flip\ j \mid Z = 1) = 1 - e_2^j$$

Thus, subscripts here indicate type I and type II errors respectively. Note that this setup admits time-varying errors. For example, there may exist times with significant information arrivial (e.g., both e_1^j and e_1^j are low) and other times during which relatively little information arrives. Define $Z(N+1) = Pr(Z = 1|N\ \textit{straight heads})$. By Bayes rule, we have

$$Z(N+1) = \frac{p\prod(1-e_2^1)...(1-e_2^N)}{p\prod(1-e_2^1)...(1-e_2^N) + (1-p)\prod e_1^1...e_1^N}$$

where p denotes the unconditional probability that $Z = 1$.

Clearly, $Z(N)$ is increasing for all N. Let J be the first time for which $e_1^J = 0$ if such a J exists. In that case, $Z(J) = 1$. Consequently there will

[4] It is assumed that without new entry, no signal is generated: one cannot observe the outcome of previous agents' innovations if there are no previous agents.

never be more than J coin flips, as all information is known about Z by this time. If instead no such J exists then we denote $J = \infty$, and coin flips may continue indefinitely.

Define p_j as the probability of a heads at time j conditional on observing (j-1) previous heads. p_j is completely determined by the primitive variables $\{e_1^j, e_2^j\}$.

Let α_i be the equity stake demanded by investors in wave i. This value will be endogenously determined. The condition for the marginal (lowest-quality) agent in the ith wave follows.

$$(1-\alpha_i)Z(i)\pi_i = p_i(1-\alpha_{i+1})Z(i+1)\pi_i + (1-p_i)V \tag{1}$$

The left side is the expected profit from entering the ith wave, i.e, after having observed (i-1) heads. On the right side, the first term reflects the probability that an (i+1)st wave will occur times the expected payoff in that event. The last term on the right-side reflects the outcome if the agent intends to waits for (i+1)st wave, only to find this wave never occurs because the coin flip at time i shows tails.

The participation constraint of investors in the ith wave is

$$\alpha_i Z_i \left(\frac{\pi_i + \pi_{i+1}}{2}\right) = K \tag{2}$$

The equilibrium variables $\{\pi_i, \alpha_i\}$ can then be obtained by solving the system of 2J linear equations given by {(1),(2)} for $i \in \{1, ..., J\}$.

2.2 A More Specialized Example

We specialize the previous example by assuming that $e_1^1 = e_2^1 = 0$, so that Z is revealed with certainty after the first wave. Agents then fall into one of three categories:

- First Wave: enter the market before Z is revealed, i.e., agents along the interval $[\pi_1, 1]$.
- Second Wave: enter only if Z=1, i.e., agents along the interval $[\pi_2, \pi_1]$.
- Abstain: do not enter the market regardless of Z's value, i.e., agents along the interval $[0, \pi_2]$.

Analogous to (1), the cutoffs π_1 and π_2 are determined by the following equations.

$$p(1-\alpha_1)\pi_1 = p(1-\alpha_2)\pi_1 + (1-p)V \tag{3}$$

$$(1-\alpha_2)\pi_2 = V \tag{4}$$

where p is the unconditional probability that $Z = 1$.

The left side of (3) is the payoff from entering in the first wave, before the coin flip. With probability (1-p) the subsequent coin flip reveals Z=0 and so the payoff is zero. With probability p instead the coin flip reveals Z=1. In this state the payoff is the agent's residual claim $1-\alpha_1$ times his quality π_i. The right side of (3) represents the payoff from waiting, and entering the second wave which occurs *only* if the coin flip is heads.

Note that p is absent from equation (4). This is because if a second wave occurs, then Z=1 for sure. The agent's payoff is simply their residual claim $1-\alpha_2$ times their (privately-known) quality. This cutoff π_2 is defined as the agent who is just indifferent between issuing and exiting the market.

Solving {(3),(4)} for $\{\pi_1, \pi_2\}$ we obtain:

$$\pi_1 = \frac{(1-p)V}{p(\alpha_2-\alpha_1)} \tag{5}$$

$$\pi_2 = \frac{V}{1-\alpha_2} \tag{6}$$

Several inequalities are needed to prevent the outcome from being degenerate. We need the following condition:

$$\underbrace{\frac{V}{1-\alpha_2}}_{\pi_2} < \underbrace{\frac{(1-p)V}{p(\alpha_2-\alpha_1)}}_{\pi_1} < 1$$

The above equation emphasizes that the market must impose an adverse selection discount on issuers that wait until the second wave (i.e., $\alpha_2 > \alpha_1$). Without such a discount, $\pi_1 > 1$. Waves would then fail to start because every agent would wait until the second round. Without any leaders, and we arrive back at the stalemate discussed in the introduction.

To complete the description of the equilibrium, we now endogenize α_i. The participation constraints of investors define the equity stakes demanded:

$$\alpha_1 \left(\frac{\pi_1 + 1}{2}\right) p = K \qquad \text{First Wave} \tag{7}$$

$$\alpha_2 \left(\frac{\pi_1 + \pi_2}{2}\right) = K \qquad \text{Second Wave} \tag{8}$$

The equilbrium $\{\pi_1, \pi_2, \alpha_1, \alpha_2\}$ is then determined by the four equation system (5)-(8). With some substitution, it can be simplified to the following two equation, two unknown system.

$$\pi_1 = \frac{V(1-p)(\pi_1+\pi_2)(\pi_1+1)}{2K[p-\pi_1(1-p)-\pi_2]} \tag{9}$$

$$\pi_2 = \frac{V(\pi_1+\pi_2)}{\pi_1+\pi_2-2K} \tag{10}$$

Theorem 1 (Comparative Statics for p) *The solution $\{\pi_1, \pi_2\}$ to the system $\{(9), 10)\}$ has the following properties.*
a) $\frac{\partial \pi_1}{\partial p} < 0$
b) $\frac{\partial \pi_2}{\partial p} > 0$

The result in Theorem 1a is intuitive. When less risk is resolved by leaders actions (i.e., high p), there is less to be gained by taking a wait-and-see approach. Thus agents tend to enter the first waves in order to avoid being indentified as low-quality. Thus, high p is associated with large first waves.

Theorem 1b is somewhat more subtle. There is no direct dependence of π_2 on p in equation (10). In particular, by the time wave 2 occurs (if at all) the probability p is no longer directly relevant. Once it has been publicly revealed that Z=1, the ex-ante probabilities of this state are sunk. Yet there is an important sense in which *history matters* in this scenario because of the following indirect effect. As p rises, π_1 falls and more agents choose to enter the first wave. Consequently, the quality of agents remaining in the second pool drops. Thus when p is high, there is a strong adverse selection effect from being identified as a second wave agent. This adverse selection effect worsens pricing in the second wave, causing π_2 to rise.

Theorem 1 implies that high p is associated with a large first wave and small second wave. Low p is associated with the opposite. These comparative static results on wave sizes are important for subsequent results.

Theorem 2 (Comparative Statics for V) *The solution* $\{\pi_1, \pi_2\}$ *has the following properties.*
a) $\frac{\partial \pi_1}{\partial V} > 0$
b) $\frac{\partial \pi_2}{\partial V}$ *is ambiguous. When p is high,* $\frac{\partial \pi_2}{\partial V} > 0$*. When p is low,* $\frac{\partial \pi_2}{\partial V} < 0$

The intuition for Theorem 2a is straightforward. As V rises, the net present value of projects falls and therefore fewer agents enter the first wave.

Theorem 2b is somewhat more subtle. The direct effect of a rise in V, as in the first wave, is to reduces agents' incentives to seek financing in general.

The indirect effect is that, as V rises, there is less of an adverse selection impact of waiting until the signal Z is revealed. In other words, the average quality of the second wave rises and the market doesn't "punish" issuers for waiting. In contrast to the direct effect, this effect tends to reduce π_2.

Which effect dominates? When p is low, there are low expectations for the possibility of a second wave. If, however, the market is pleasantly surprised to see $Z = 1$, then it takes a relatively forgiving approach to those agents who waited until the second round. (In effect, their hesitation had more to do with uncertainty about the public signal rather than pessimism about their private signal.) To see this claim mathematically, note that which effect dominates depends on how sensitive the endpoint π_1 is to p (i.e., how strong the indirect effect is). Re-writing equation (3) as

$$p\,(\alpha_2 - \alpha_1)\,\pi_1 = (1-p)V$$

reveals that when p is low, the endpoint π_1 is highly senstive to V. Thus, the indirect effect is strong and so dominates the direct effect. In that case, the comparative statics π_1 and π_2 exhibit opposite signs.

Overall, the effect of internal capital is to shrink the size of the first wave but not (necessarily) the second wave. This recalls the intuition of the stalemate discussed in the introduction: *internal capital makes people followers in risky situations.* If one can observe the outcome of others' experiments, it makes more sense to follow than to lead. It is now shown that the comparative statics with respect to K (external capital) tell a different story.

Theorem 3 (Comparative Statics for K) *The solution $\{\pi_1, \pi_2\}$ to equations (7) and (8) has the following properties.*
a) $\frac{\partial \pi_1}{\partial K}$ is ambiguous. When p is high, $\frac{\partial \pi_1}{\partial K} < 0$. When p is low, $\frac{\partial \pi_1}{\partial K} > 0$.
b) $\frac{\partial \pi_2}{\partial K} > 0$.

Theorems 2 and 3 are highly symmetric. In both cases, an endpoint unambiguously moves upward in respose to an increase in cost, whereas the other endpoint's movement is ambiguous. The explanation for this ambiguity likewise involves discussing tradeoffs between a direct effect (i.e., an increase in costs leads to fewer entrants) and an indirect effect which occurs through a change in the quality of the other wave. In this case, however, the cost K is not borne directly by issuers. Rather it is borne indirectly through α_i. Thus we investigate its effect by examining equations (7) and (8) rather than (5) and (6).

Clearly, as capital costs rise, the net present value of projects drop and therefore fewer agents seek funding in general. Less obvious is how this shock changes the *relative* attractiveness of entering wave 1 and wave 2. To examine this question, recall that when p is high in general, agents tend to enter the first wave. This implies that the average quality of agents in the second wave is low. Now, from equations (7) and (8), we see that $alpha_2$ is quite sensitive to K in these cases much more so than is $alpha_1$. Consequently, though an increase in K makes both waves less attractive, it does so disproportionately for wave 2. An increase in K therefore causes an exodus out of wave 2 and into wave 1.

This result constitutes a key piece of intuition: *reliance on external capital encourage agents to innovate early.*

3 Conclusions

This paper develops a dynamic theory of the incentive to innovate, when there are both public and private signals about the returns to innovation.

Internal financing leads to a stalemate in which all agents enter a waiting game, hoping for others to innovate first. This incentive arises because information is a public good, and thus waiting allows others to (partially) resolve risk for their own projects. When using external financing, the terms of financing depend upon the investors assessment of the issuers quality. As shown here, this financing game leads to an orderly and predictable process in which firms enter the market in order of their privately-known quality (highest to lowest). This feature creates, in effect, a rush to innovate early as high-quality agents signal their quality and obtaining better financing terms.

The binary payoffs in the paper imply that, without loss of generality, all securities may be described as equity. The intuition would seem to extend in a straightforward manner to address the question of how capital structure affects innovation. In particular, riskless debt functions effectively like internal financing. According to Theorem 3, then, debt would tend to decrease the amount of innovation whereas equity-like securities – more generally, any security which is information-sensitive – would tend to increase innovation. The key property is information-sensistivity because this determines the extent to which the investor cares about the quality of the firm being financed; i.e., the sensitivity of security pricing to firm quality.

As mentioned in the introduction, there is a substantial economics literature examining the connection between innovative activities and the structure of product market competition. The connection between these two is clear: the nature of product market competition – i.e., a characterization of the competitors' responses – determines the size and duration of Schumpterian rents. To my knowledge, these papers have not considered the role of the source of finance. The model in this paper illustrates the incentive to innovation also depends upons the relative balance of internal and external finance.

In the academic finance literature, it seems to be nearly a folk result that innovative activity is disproportionately a function of small firms reliant on outside finance. For example, Kortum and Lerner (2000) point out that the ratio of venture capital to total industrial R&D is less than 3%, yet venture capital accounts for 15% of industrial innovations. Results such as these beg the question of causality: are these firms may be innovative because they are small and nimble, with reliance on external financing merely a side effect of their size?

More recent research is instead consistent with a causal connection. Brown, Fazzari and Peterson (2009) find that the 1990s R&D wave was almost entirely driven by seven industries that experienced large influxes of equity capital. Futhermore, most of the shock was due to the behavior of new entrants in the industry (who actually relied on external finance) rather than incumbents, who were presumably more likely to finance their R&D internally. Brown and Peterson (2009) find that in the years following these R&D waves, incumbents tend to lose market share of sales. This finding is consistent with the model's prediction that first-movers are of higher quality.

Lerner, Sorensen and Stromberg (2008) find no decrease in R&D expenditures following private equity LBOs – a time of great pressure for cost-cutting measures. Indeed, they found that the number of influential innovations (as measured by patent citations) significantly increased following the private equity investment. Also consistent with the theme of this paper, Atanassov, Nanda and Seru (2007) find significant increases in innovative activity following arms-length financings, and also find that the innovations are more influential.

It is also worth noting the inconsistency of the latest wave of research with Schumpeter (1942), the theory of innovation that he developed in his later years. Recall that in his original theory, Schumpeter (1912), innovation is attributed to the entrepreneurial spirit "Unternehmergeist." Creative destruction occurs because of visionaries who primarily need brilliance and luck rather than economic incentives. By contrast, Schumpeter (1942) recognizes the central role of intellectual property rights. If ideas can be easily stolen or imitated, then the incentive to invest in innovative research is diminished. Indeed, he argues that this is a potential benefit of monopolies (for all their downsides): the protection of product market power leaves the incentive for R&D.

This paper introduces a new layer of discussion to the argument between Schumpeter (1912) and Schumpeter (1942). The incentive to innovate also depends upon the source of finance. Note that, by design, product market competition is entirely absent from this paper in order to focus on the effect of financing. That is, I do not introduce a product-market-related benefit to being a first-mover. Even so, high-quality firms still choose to innovate early. What is not obvious is whether there are any interactions between the product market version of Schumpterian rents and the financing channel identified here.

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Table 1, Panel A: Financing Models with Exogenous Ordering of Issuance

	Issuer Heterogeneity (which characteristic)?	Allocation of Information	Advantage of Leading	Advantage of Following
Hoffman-Burchardi (2001)	Firm Quality	Investors produce costly information as in Chemmanur (1993)	None	Reduces IPO underpricing, as followers free-ride on investors' information production costs borne by leaders. In addition, information at T=1 reveals the riskiness of projects at T=2. With risk-averse entrepreneurs, this revelation may trigger a wave of risk-induced sales.
Benveniste, Busaba and Wilhelm (2002)	None	All info is public	Underwriters endogenously create one by taxing followers, preventing market failure.	Underwriters endogenously create one by taxing followers, preventing market failure.

Table 1, Panel B: Financing Models with Endogenous Ordering of Issuance

	Issuer Heterogeneity (which characteristic)?	Allocation of Information	Advantage of Leading	Advantage of Following
Persons and Warther (1997)	Cost of adopting new technology	All info is public	Time value of money (pure cost of delay)	Obtain info about the value of the project. Decision to enter/exit is therefore more informed.
Alti (2005)	Timing of capital needs and probability of finding a project	Investors endowed with heterogeneous information as in Rock (1986)	Projects expire if unfunded; the IPO market stochastically shuts down.	Reduces IPO underpricing. Information revealed at T=1 mitigates subsequent informational frictions (early IPO prices reveal investors' private information).
Pastor and Veronesi (2005)	Time to expiration of patent	All info is public	Time value of money; limited time until patent expires	Time value of money; limited time until patent expires

5 Proofs

Proof of Theorem 1. I derive the comparative static result $\frac{\partial \pi_1}{\partial p} < 0$ here. $\frac{\partial \pi_2}{\partial p} < 0$ is similar. Rewrite (9) and (10) as

$$F := \pi_1 2K[p - \pi_1(1-p) - \pi_2] - (1-p)(\pi_1 + \pi_2)(\pi_1 + 1) = 0$$

$$G := \pi_2(\pi_1 + \pi_2 - 2K) - V(\pi_1 + \pi_2) = 0$$

Totally differentiating this system with respect to p, one obtains

$$\frac{\partial F}{\partial p} + \frac{\partial F}{\partial \pi_1}\frac{\partial \pi_1}{\partial p} + \frac{\partial F}{\partial \pi_2}\frac{\partial \pi_2}{\partial p} = 0 \tag{11}$$

$$\frac{\partial F}{\partial p} + \frac{\partial F}{\partial \pi_1}\frac{\partial \pi_1}{\partial p} + \frac{\partial F}{\partial \pi_2}\frac{\partial \pi_2}{\partial p} = 0 \tag{12}$$

Now, the above is a system of two equations to be solved for two unknowns $\frac{\partial \pi_1}{\partial p}$ and $\frac{\partial \pi_2}{\partial p}$. Solving the system, one obtains:

$$\frac{\partial \pi_1}{\partial p} = \frac{\frac{\partial G}{\partial p}\frac{\partial F}{\partial \pi_2} - \frac{\partial G}{\partial \pi_2}\frac{\partial F}{\partial p}}{\frac{\partial F}{\partial \pi_1}\frac{\partial G}{\partial \pi_2} - \frac{\partial G}{\partial \pi_1}\frac{\partial F}{\partial \pi_2}} \tag{13}$$

Reporting only the signs of each of these partial derivatives,

$$sign\left(\frac{\partial \pi_1}{\partial p}\right) = \frac{0 \ominus - \oplus \oplus}{\oplus \oplus - \oplus \ominus} < 0 \tag{14}$$

Q.E.D.

Proof of Theorem 2. Part a) is similar to Theorem 1. To derive part b) note that

$$\frac{\partial \pi_2}{\partial V} = \frac{\frac{\partial G}{\partial V}\frac{\partial F}{\partial \pi_1} - \frac{\partial G}{\partial \pi_1}\frac{\partial F}{\partial V}}{\frac{\partial F}{\partial \pi_2}\frac{\partial G}{\partial \pi_1} - \frac{\partial G}{\partial \pi_2}\frac{\partial F}{\partial \pi_1}} \tag{15}$$

Reporting the signs of each of these partial derivatives,

$$sign\left(\frac{\partial \pi_2}{\partial V}\right) = \frac{\ominus \oplus - \oplus \ominus}{\ominus \oplus - \oplus \oplus} = \frac{?}{\ominus} \tag{16}$$

which is ambiguous. However, one can show that the numerator in (16) is decreasing in p. Moreover, when p=1 we have $\frac{\partial F}{\partial V} = 0$ so that the numerator is negative, and therefore the fraction itself is positive. When instead p=0 the numerator simplifies to

$$2K(\pi_1 + \pi_2)(1 - \pi_2) > 0 \tag{17}$$

so the fraction is negative. The proof of Theorem 3 is similar.

Q.E.D.