Optimal Financing for R&D-intensive Firms

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This Draft: October 29, 2015

Abstract

The combination of large capital requirements, long gestation lags, low probabilities of success poses unique challenges for modeling the financing decisions of many R&D-intensive firms, such as biopharmaceutical companies. We construct an optimal capital structure model of firms in R&D-intensive industries that explains several key stylized facts of these industries, including underinvestment in early stage R&D, and propose a new financing mechanism to reduce the incentives for underinvestment. Our framework incorporates adverse selection and moral hazard, with the possibility of reducing some of the adverse selection through directly verifiable voluntary information disclosure. But this information disclosure involves a “two-audience” signaling problem, leading to a higher probability of competitive entry associated with greater disclosure. We establish the optimal pecking order of securities with direct market financing when such disclosure partially endogenizes the extent of adverse selection. Under plausible conditions, equity dominates debt and firms raise enough financing to carry excess cash. However, market financing still leaves some potentially valuable R&D investments unfunded. We then take a mechanism design approach, with a binding precommitment by firm insiders to make costly ex post payouts, and show that a mechanism consisting of put options can be used in combination with equity to eliminate underinvestment in R&D and improve welfare relative to the direct market financing outcome. The optimal mechanism consists of bilateral “insurance” contracts, with investors offering firms insurance against R&D failure and firms offering investors insurance against very high R&D payoffs not being realized.

Keywords: R&D Investments; Healthcare Finance; Pharmaceutical Industry; Biotechnology Industry; Capital Structure; Information Disclosure; Mechanism Design

JEL Classification: D82, D83, G31, G32, L65, O32

*We thank Michael Abrahams, Asaf Bernstein, Hui Chen, Xavier Giroud, Daniel Green, Jack Liebersohn, Debbie Lucas, Daniel Saavedra Lux, Andrey Malenko, Stew Myers, Jonathan Parker, and seminar participants at MIT for helpful comments and discussions. Any remaining errors are our own. Research support from the MIT Laboratory for Financial Engineering is gratefully acknowledged. The views and opinions expressed in this article are those of the authors only and do not necessarily represent the views and opinions of any other organizations, any of their affiliates or employees, or any of the individuals acknowledged above.

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1 Introduction

What is the optimal way for an R&D-intensive firm to finance itself? This question is of critical importance given the social value that R&D investments carry—for example, large-scale R&D investments in pharmaceutical and biotechnology firms are essential for the development of new life-saving therapies, and new technological innovations are a key driver of economic growth. However, despite the importance of investments by such R&D-intensive firms, there is evidence of a “funding gap” for investment and innovation that creates underinvestment in R&D, which is only partly mitigated by the presence of venture capital (see Hall and Lerner (2010)). As a result, many potentially transformative innovations are never realized. This funding gap raises the question of what the optimal mix of financing is for R&D-intensive firms and whether there is a market failure that systematically creates a “Valley of Death” for early stage R&D funding. We address this question theoretically in this paper.

Some of the reasons that have been suggested for this funding gap are the unique features of R&D-intensive firms. There are four observably unique features of such firms:

1. They invest considerably more in R&D than other firms, with very high investment costs for each project. For example, recent estimates suggest that the development cost of a single new drug in the biopharmaceutical sector is $2.6 billion (see DiMasi, Grabowski, and Hansen (2014)).

2. Their R&D investments often have long gestation periods consisting of multiple phases...

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1 Brown, Fazzari, and Petersen (2009) empirically document a significant link between financing supply and R&D. Lerner, Shane, and Tsai (2003) show that biotechnology firms are more likely to fund R&D through potentially inefficient alliances during periods of limited public market financing. Thakor et al. (2015) document that pharmaceutical and biotechnology companies have a significant exposure to how well the economy is doing. See also Fernandez, Stein, and Lo (2012) and Fagnan, Fernandez, Lo, and Stein (2013), who argue that R&D has become more difficult to finance through traditional methods, and thus that more innovative financing methods are needed to continue drug development in the future.

2 DiMasi and Grabowski (2007) estimated the average capitalized cost of a new drug to exceed $1 billion as of the mid-2000’s, suggesting that this cost has been increasing over time. It is not uncommon for a pharmaceutical firm to invest fifty times as much in the R&D needed to develop a new drug as it does in the property, plant, and equipment to manufacture the drug.
of binary outcomes, in contrast to the more continuous investment processes in other industries such as manufacturing. Moreover, their R&D investments involve a sequence of escalating resource commitments, and require substantial specialized knowledge (see DiMasi, et al. (1991)).

3. Their R&D investments generally have low success probabilities (see DiMasi et al. (1991, 2013), but high payoffs conditional on success (e.g. Grabowski, Vernon, and DiMasi (2002) and DiMasi, Grabowski, and Vernon (2004)).

4. Because of the large R&D outlays required, R&D-intensive firms must rely on external financing.³

This last feature of R&D-intensive firms also exposes them to a number of financing frictions that have been identified in the literature. These include adverse selection (uncertainty about the quality or payoff potential of the R&D) and moral hazard (uncertainty about whether the firm will invest in commercially viable R&D or “castle-in-the-sky” R&D that has little commercial value), as well as “two-audience” information disclosure signaling costs—firms must disclose information about their R&D pipeline to investors to obtain financing at reasonable terms, but this same information also becomes available to competitors thereby diminishing the value of R&D (e.g. Bhattacharya and Ritter (1983)).⁴ These financing frictions alone have important implications for the capital structure choices of firms, but the combination of these frictions with the unique features of R&D-intensive firms makes their optimal financing choices unclear.

In this paper, we develop a theory of optimal financing that takes into account the unique features of investments of R&D-intensive firms as well as the financing frictions that

³See Lerner, Shane, and Tsai (2003) and Brown, Fazzari, and Petersen (2009) for empirical evidence of the reliance of these firms on the broader equity market. Also see Thakor et. al. (2015) for empirical evidence of this for pharmaceutical and biotechnology companies.

⁴See Jones (2007), for example, for empirical evidence on the costs and benefits of information disclosure for R&D-intensive industries. In this paper, we focus on the costs of direct and verifiable disclosure. There may also be product-market-spillover costs associated with firms signaling to the financial market through, say, capital structure as in Gertner, Gibbons, and Scharfstein (1988).
they face. Our model explains four important stylized facts about R&D-intensive firms. First, these firms use very little leverage in their capital structure (e.g. Himmelberg and Petersen (1994) and Thakor and Lo (2015)), and there is a negative correlation between leverage and R&D investments (e.g. Bradley, Jarrell, and Kim (1984)). Second, there appears to be underinvestment in R&D, even by firms that are publicly-traded and have access to the capital market (see Hall and Lerner (2010)). Third, these firms tend to hold large cash balances (e.g. Thakor and Lo (2015); also see Brown and Petersen (2011) and Bates, Kahle, and Stulz (2009) for evidence that greater R&D intensity leads to higher cash balances). Fifth, R&D-intensive firms rely on stock issues to finance R&D—see Brown, Fazzari, and Petersen (2009)—and hence do not display the often-discussed aversion of other firms to equity issuance (e.g. Admati, DeMarzo, Hellwig, and Pfleiderer (2015)).

The standard theoretical argument for why R&D-intensive firms avoid debt tends to rely on the limited collateral value of knowledge assets (e.g. Hart and Moore (1994) and Rampini and Viswanathan (2010)). But R&D-intensive firms are able to rely on their stock of knowledge patents as a source of collateral (see Mann (2014)), making their relatively light use of debt more puzzling.

Using these unique features of R&D-intensive firms and the various frictions they face in raising external financing, we develop a model that produces a new “information-and-financing” pecking order for these firms compared to the pecking order identified by Myers and Majluf (1984). As in the standard pecking-order argument, the most preferred way to finance investments is with internal cash (retained earnings), which is documented as an important financing source for R&D by Brown, Fazzari, and Petersen (2009). When the R&D is sufficiently valuable, the next most preferred way to finance investments is with equity, with an endogenously-chosen level of information disclosure. The least preferred way to finance is with debt. A key feature of this pecking order is that the firm raises all the

5 He and Wintoki (2014) document that the sensitivity of cash holdings to R&D investments among R&D-intensive firms has increased dramatically in the last 30 years, and that increased competition seems to be a major driver of this, which is consistent with the argument of Thakor and Lo (2015).

6 This pecking order is based on the assumption that the firm has no assets other than the option to invest
financing it needs for the initial investment as well as for anticipated future investments when the amount of private information that it has about its R&D idea is the smallest, and then carries what it does not invest right away as excess cash. Thus, a large cash balance emerges endogenously.

The intuition is as follows. Internal financing is most preferred because it avoids both the adverse selection and information-disclosure costs of external financing. Equity is preferred to debt for two reasons. The first is that the undertaking of valuable R&D with a low success probability by the firm substantially shrinks the benefit of debt while exacerbating the cost of debt. The benefit of debt is that the bondholders can reduce the likelihood of the manager mis-using funds by pursuing inefficient investments for personal benefit (rather than valuable R&D). This is the standard disciplining role of debt (e.g., Hart and Moore (1995)). The cost of debt is that bondholders are not infallible—they sometimes fail to detect managerial misuse of funds and sometimes incorrectly view a legitimate and valuable R&D project as a misuse of funds. Given the highly specialized knowledge associated with R&D for these firms, the cost of liquidation due to erroneous bondholder assessments is particularly germane. In our model, the bondholders become more error-prone as the probability of success of R&D declines. This reduces the benefit of debt while increasing its cost. When R&D becomes sufficiently valuable, the cost of debt exceeds the benefit.

The second reason why equity is preferred to debt is that the value of equity is more sensitive to changes in information disclosure than is the value of debt. This implies that debt requires a higher level of optimal information disclosure than equity in equilibrium. The resulting higher loss of firm value from two-audience signaling costs adds to the unattractive in R&D. As a result, the Myers and Majluf (1984) pecking order does not arise here in part because we have no assets in place in our model. The presence of assets-in-place would create a role for debt financing to sometimes be preferred to equity. Other papers have also explored the optimal choice of security in a similar setting of pure adverse selection related to asymmetric information, and have shown that the Myers and Majluf (1984) pecking order may be overturned under different assumptions. See, for example, Brennan and Kraus (1987), Noe (1988), Nachman and Noe (1994), and Fulghieri, Garcia, and Hackbarth (2013). However, in contrast to these papers, we incorporate a number of additional frictions as well as unique features of R&D-intensive firms, and explore the optimal choice of security when these features interact.

7This is consistent with the intuition of papers that have argued that debt is informationally-insensitive. See Holmstrom (2015) for a review.
tiveness of debt relative to equity. We also show that the second-best level of information disclosure is an interior optimum, so there is no residual incentive to disclose further information for signaling purposes (i.e. for firms to separate themselves from bad firms through additional disclosure). This is one important distinguishing feature of our model compared to the usual capital structure models.

The reason why the firm raises more financing than it needs for immediate investment is that the more the firm knows relative to the market, the more its disclosure will reveal to its competitors. Information-disclosure-related losses will thus be greater the more the firm knows. Since raising external financing conveys information, it is better for the firm to raise as much financing as it can at the outset when its knowledge of what the R&D will produce is relatively low, rather than later when it will know more. Thus, biopharma firms will typically carry large (excess) cash stockpiles. This provides a justification for large cash holdings for such firms that is distinct from precautionary motives for holding cash.\(^8\)

There are a few points worth noting about information disclosure in this setting. In many cases, a firm’s R&D in its early stages may not yield enough information for a patent to be filed. As a result, any disclosure may be particularly damaging. In the U.S., the patent law system allows firms to file some patents (such as those for drug compounds) relatively early on in the R&D process—and through filing a patent, a firm both discloses public information about the nature of the R&D and also gains protection over its eventual product.\(^9\) As a result, a natural question that arises is: why should a firm fear additional information disclosure? There are two reasons for why information disclosure is still a salient issue for these firms. First, while patents can protect intellectual property, they do not necessarily guarantee market exclusivity. For example, with drug development, a firm can only file for market

\(^8\)For example, Bolton, Chen, and Wang (2014) develop a model in which firms have a precautionary demand for liquidity, and thus build up cash reserves and hold low levels of debt in order to prevent liquidity from being drained for debt servicing. In contrast, we focus on the role of information disclosure costs in inducing firms to hold excess cash—thus, a firm in our setup will want to hold cash to avoid disclosure even if it has no need to protect against future bad states. Moreover, in our framework, firms also maintain low leverage due to the shortcomings of debt as a disciplining device.

\(^9\)In addition, specifically for biopharma firms, the results of clinical trials are required to be reported to the FDA, and then publicly disclosed.
exclusivity once a drug has passed the final phase of approval with the FDA. However, until that point in time, there is the possibility of another firm getting to that phase in less time.\footnote{Since the Hatch-Waxman Act of 1984, drug developers could skip the first few phases of clinical trials so long as some other firm has shown bioequivalence. This system was put into place in order to strike a balance between encouraging innovation (through market exclusivity) and allowing generic drugs to enter into the marketplace.} Second, even after filing a patent, there are some aspects of the firm’s R&D that the firm knows more about than its competitors, and this informational advantage can be eroded via information disclosure. As an example, a biopharma firm may disclose information about a particular organic compound through a patent filing (or alternatively the results of clinical trials may be disclosed once filed with the FDA), but the firm itself may still retain precise knowledge of how promising the results are, alternative applications of the drug, and other specifics which increase the commercial value of the R&D.

While we permit information disclosure to reduce some information asymmetry, we also recognize that there may be some aspects of R&D that the firm knows more about than the market, and its voluntary information disclosure does nothing to lessen this information asymmetry. We model this by assuming that the firm can make an additional investment in R&D that can enhance its expected cash flow from the R&D, and that the firm’s insiders know more about the extent of the cash flow enhancement due to this investment than do investors. Since information disclosure cannot reduce this information asymmetry, only a pooling outcome is possible, and this leads to all firms avoiding this additional R&D investment. This rationalizes the empirically-documented underinvestment in R&D (see Brown and Lerner (2010)), and leads to a welfare loss since this investment is both privately and socially valuable for some firms.

This “R&D funding gap” with market financing motivates the next part of our analysis. We explore whether it is possible to improve upon the traditional capital market funding of biopharma firms. We introduce a hypothetical “arbiter” who is able to extract a \textit{binding precommitment} from the firm’s insiders to make costly \textit{ex post} payouts from their personal wealth endowment (thereby effectively relaxing the firm’s limited liability constraint) and de-
sign a mechanism to elicit truthful reports from firms about their private information related to the extent of the expected cash flow enhancement from the additional R&D investment.\textsuperscript{11} This mechanism involves a put option on the firm’s value that has a digital option attached to it such that the firm’s insiders are long in the option and outside investors are short in the option over some range of firm values, whereas insiders are short in the option and outside investors are long in it for all other firm values. The core intuition behind the mechanism design is as follows. Firm insiders are asked to report how likely their additional R&D investment is to succeed, and are also asked to provide investors “insurance”, i.e., a put option, against the possibility that the firm’s R&D fails to achieve relatively high cash flows. The amount of insurance that insiders must provide is greater if the firm reports a higher probability that its additional R&D investment will succeed. The mechanism thus deters insiders from misrepresenting themselves as having high probabilities of achieving very high cash flows, and (partially) protects investors against the firm’s failure to realize very high R&D cash flows. However, since R&D outcomes are uncertain, providing such insurance to investors is costly for the firm’s insiders. To offset this cost, the mechanism also includes a put option offered by the firm’s investors to the firm’s insiders, which insures the insiders against very low cash flows. That is, through the mechanism investors are provided a stronger assurance of a relatively high upside while insiders are provided stronger protection against the downside.\textsuperscript{12} Thus, potential underinvestment in R&D is discouraged from both the standpoint of insiders underinvesting due to high possibility of failure, and investors underinvesting due to suspicion of too low a probability of very high payoffs (adverse selection).

We argue that these options function as a bilateral insurance contract between investors and insiders, enabling them to protect each other against undesirable outcomes, and thus allowing firms to make welfare-enhancing R&D investments. While the idea of insurance against failure provided to entrepreneurs/insiders is reflected in some existing contracts, as

\textsuperscript{11}The government or a third-party entity such as an exchange could play the role of arbitrator.
\textsuperscript{12}Although we do not have risk aversion in our model, this has an interesting interpretation in terms of encouraging risk-averse entrepreneurs to invest in R&D.
we discuss later, a novel normative aspect of our mechanism design is the put option sold by insiders to investors. We also relate these options to some recently proposed biopharma innovations like “FDA swaps” (see Philipson (2015)) and “phase 2 development insurance”. Our analysis reveals the potential benefits of coordinating mechanisms between firms and investors that can induce precommitment in R&D financing.

While our analysis focuses on R&D-intensive firms like biopharma firms, it also has broader implications for capital structure and financing decisions in other industries where the probability of success is low, but the payoff conditional on success is high, and projects involve considerable technical expertise. The film industry is one such example, and novel financing mechanisms have already emerged in that industry along the lines predicted by our model.

In Section 2 we review the related literature, and we introduce our model in Section 3. Section 4 contains the direct market financing analysis, as well as a discussion of an extension of the model in which debt may be used if the firm has assets in place. Section 5 contains the mechanism design analysis. We conclude in Section 6.

2 Related Literature

Our model is directly related to the vast theoretical literature on optimal capital structure for firms. Starting with the seminal paper by Modigliani and Miller (1958) on the irrelevance of capital structure in a frictionless environment, subsequent papers have focused on how various frictions may push firms towards a certain optimal mix of debt and equity. Jensen and Meckling (1976), Miller (1977), Myers (1977), Leland and Pyle (1977), Myers and Majluf (1984), Zweibel (1996), Bolton, Chen, and Wang (2014), Abel (2014), and Admati, DeMarzo, Hellwig, and Pfleiderer (2015), among others, all propose theories of optimal capital structure based on the role of frictions stemming from asymmetric information, agency problems, adverse selection, or tax distortions. For more complete reviews, see Harris and Raviv
(1991), Frank and Goyal (2005), and Myers (2001). While this paper also examines optimal capital structure in the presence of asymmetric information and agency problems, our model focuses on how these frictions interact with the unique features of the biopharma industry to deliver different predictions about optimal capital structure for these firms. Moreover, in the context of the disciplining role of debt, our analysis highlights a novel limitation/cost of debt in firms that engage in highly-specialized R&D. Specifically, we show that as the probability of success of the R&D declines, the efficacy of debt as a disciplining device declines, and the cost of type-1 errors in exerting discipline goes up. This sheds new light on why R&D-intensive firms like biopharma firms use low leverage.

Our model is also related to a number of theoretical papers which have examined incentives, decision-making, and contracts in R&D-intensive firms. Aghion and Tirole (1994) use a contracting framework to examine the organization of R&D firms. While their focus is on the allocation of property rights and types of contracts that arise in such firms, our focus in this paper is on the optimal financing of R&D in biopharma firms. Bhattacharya and Ritter (1983) point out the importance of disclosure with respect to R&D, while Bhattacharya and Chiesa (1995) examine the conditions under which R&D firms may disclose information when they are looking to banks for funding. Our paper incorporates information disclosure in its analysis, but also looks at how the interaction between information disclosure and other frictions affects the funding decisions of biopharma firms in the public debt and equity markets. Gertner, Gibbons, and Scharfstein (1988) develop a model in which the firm’s capital structure potentially signals proprietary R&D information to product-market competitors. In contrast to that paper, capital structure does not play a signaling role in our analysis since it communicates no information beyond that contained in direct and verifiable disclosure. In addition, we also examine how a mechanism may be used to improve the optimal amount invested in R&D. And Myers and Read (2014) examine financing policy in a setting with taxes for firms with significant real options. While the R&D projects of biopharma firms can be viewed as real options, we take a different theoretical approach in order to focus on
frictions related to asymmetric information and moral hazard.

A related paper is Thakor and Lo (2015), which examines a biopharma firm undertaking a staged investment, and provides empirical evidence. In contrast to this paper, Thakor and Lo (2015) focus on the effect of competition on the risk characteristics, investment in R&D vs. assets-in-place, cash holdings, and capital structure of R&D-intensive firms and provide empirical tests of those predictions. Furthermore, our paper also contains an intentionally normative contribution—the mechanism design, which is a significant extension intended to reduce the underinvestment problem plaguing several R&D-intensive industries.

Our analysis is also related to the mechanism design literature—see Myerson (1979, 1982) and Baron and Myerson (1982) for important early contributions, and Tirole (2012) and Phillipon and Skreta (2012) for more recent contributions. While we also take a mechanism design approach in this paper, we focus on how a mechanism may improve biopharma R&D outcomes beyond existing market financing options. To our knowledge, this has not previously been explored in the literature.

3 The Model

Consider an economy in which all agents are risk neutral and the riskless rate is zero. There are R&D-intensive firms, each of which has no assets in place or external cash at the beginning, date $t = 0$. The initial owners of the firm have some personal assets (not part of the firm) that are illiquid at $t = 0$ and will deliver a payoff of $\Lambda \in \mathbb{R}_+$ at $t = 3$ if held until $t = 3$. These assets, if liquidated at $t = 0$, can be used by the initial owners of the firm to self-finance the necessary investment in R&D that the firm needs to make at $t = 1$. However, because these personal assets are illiquid, they will fetch only $l\Lambda$ if liquidated at $t = 0$, where $l \in (0, 1)$.

The firm needs $\omega R$ in capital at $t = 1$ to make the initial investment in R&D to develop a new idea, conduct clinical trials, etc., where $\omega \in (0, 1)$ and $R > 0$. If the clinical trials
and other exploratory research financed by the initial investment $\omega R$ deliver good results, then the firm will make a bigger subsequent investment of $R$ in R&D at $t = 2$; otherwise it will cease further investment. The initial investment of $\omega R$ does not produce any cash flow. Its value lies solely in what it reveals about the payoff prospects of the bigger investment at $t = 2$. This setup mimics the staged R&D investment setup that is typical in R&D-intensive firms such as biopharma firms, which conduct multiple phases of drug development, each with escalating resource commitments.

Let $q \in (0, 1)$ be the probability assessment at $t = 0$ that the initial R&D will yield good results ($G$) at $t = 2$ and $1 - q$ the probability that it will yield bad results ($B$) at $t = 2$. If the R&D yields good results, then investing $R$ at $t = 2$ will generate a probability $\delta \in (0, 1)$ of achieving a high cash flow distribution, i.e., the terminal (date $t = 3$) cash flow $x$ will have a cumulative distribution function $H$ with support $[x_L, x_H]$ and $x_L > 0$. With good results there is a probability $1 - \delta$ of achieving a low cash flow $x$ that has a cumulative distribution function $L$ with support $[0, x_L]$. It is assumed that

$$\int_{x_L}^{x_H} x \, dH > R[1 + \omega], \quad (1)$$

and

$$\int_0^{x_L} x \, dL = R + \varepsilon, \quad (2)$$

where $\varepsilon > 0$ is an arbitrarily small positive scalar. The idea is that, with a good result, the lowest expected payoff equals the second-stage investment plus a small amount. If the R&D yields bad results (failure), then any investment at $t = 2$ leads to a zero cash flow almost surely at $t = 3$. The final commercial outcome of the R&D project conditional on success, therefore, may be either a “blockbuster” (with cash flows given by (1)) or a much smaller commercial success (barely surpassing investment costs).\(^{13}\)

If, and only if, the firm invested $\omega R$ at $t = 1$ will it have an opportunity to learn whether

\(^{13}\)For the case of drug development in biopharma firms, this is consistent with the empirical evidence of Grabowski and Vernon (1990).
the outcome of the initial R&D is good or bad at \( t = 2 \). If it does not invest \( \omega R \) in the initial R&D, then it learns nothing at \( t = 2 \) almost surely. In other words, the initial investment in R&D is a necessary and sufficient condition for deciding at \( t = 2 \) whether it is worth proceeding further with the project.

Finally, if the firm invests \( R \) at \( t = 2 \), it also has the opportunity to invest an additional additional \( \Delta R \) at \( t = 2 \). If it does so, then there is a probability \( r \in [r_a, r_b] \) that the high cash flow distribution (given by (1)) can be enhanced from \( H \) to \( J \), where \( J \) is distributed over the support \( [x_H, x_J] \). That is, if the firm invests an additional \( \Delta R \) in R&D at \( t = 2 \), then in the state in which the R&D yields good results and the firm has a high cash flow distribution (joint probability \( q_\delta \)), there is a probability \( r \) that \( x \) will be distributed according to \( J \) and a probability \( 1 - r \) that it will be distributed according to \( H \), where \( J \) first-order-stochastically dominates \( H \). This R&D-enhancement can be interpreted as an alternate commercial application of the R&D project that can be revealed with additional exploration. For example, a given medicinal compound that is targeted for a particular disease may also have wider (and potentially socially valuable) applications that were not initially considered at the start of the project, and these applications may be confirmed with additional exploration or expanded trials.

In Figure 1, we graphically summarize the setup of staged R&D investment in the model.

### 3.1 The Firm’s Initial Investment Decision

At \( t = 0 \), the firm’s initial owners determine how much external financing to raise, the capital structure of the firm, and the firm’s decision of how much information, \( \xi \), to disclose. The firm chooses between debt and equity for its capital structure at \( t = 0 \); both debt and equity investors’ claims are paid off at \( t = 3 \), although bondholders may demand early repayment of debt at \( t = 2 \). At \( t = 2 \), after observing the outcome of the first-stage R&D, the firm may choose to raise additional external financing through debt and/or equity. The financing
$\text{Invest } \omega R$

$\text{Success}$

$q$

$1 - q$

$\text{Failure}$

$\text{Stop investment}$

$t = 1$

$\text{Invest } R + \Delta R$

$\delta$

$1 - \delta$

$t = 2$

$t = 3$

$\text{x } \sim \text{H}$

High Cash flow

$\text{x } \sim \text{L}$

Low Cash flow

$\text{x } \sim \text{J}$

Enhanced Cash flow

$\text{x } \sim \text{H}$

High Cash flow

$\text{x } \sim \text{L}$

Low Cash flow

$\text{Figure 1: Summary of R&D Investment Timing}$
decisions are made by the firm’s owners, while all other decisions are made by a manager, who
privately observes the signal at $t = 1$ about whether a worthwhile R&D project is available,
and then privately observes the signal about whether the first-stage R&D produced a good
or a bad outcome at $t = 2$, and whether such a signal was received in the first place. Thus,
it is the manager who decides whether to invest $\omega R$ in the first-stage R&D at $t = 1$
and whether to invest $R$ in the second-stage R&D at $t = 2$ or keep the cash idle.

This specification of decision control seems natural to us. The initial owners (insiders)
make the important strategic decisions about capital raising, capital structure, and informa-
tion disclosure. But the details of R&D are technical in nature and thus delegated to the
manager who possesses the necessary expertise to evaluate whether the first-stage R&D was
successful and whether more resources should be committed to the R&D. This is related
to an important assumption in our analysis: the R&D conducted by the firm relies on and
generates highly specialized knowledge that the financiers may lack.

### 3.2 Informational Frictions

The model has three informational frictions. The first is that, at $t = 0$, there is a possibility
that the firm is “sound”, in which case it has the opportunities described above, and there
is also a possibility that it is “unsound”. An unsound firm has no idea worth investing in
via R&D, so it will simply raise external financing at $t = 0$ and consume it. The common
prior belief is that the probability that the firm is sound is $s \in (0.5, 1)$ and the probability
that the firm is unsound is $1 - s$. The firm, its initial owners, and its manager know whether
it is sound or unsound, but this is private information; investors cannot distinguish between
sound and unsound firms.

The second informational friction is that, within the set of sound firms, there is unobserv-
able heterogeneity with respect to $r$, the probability that the the high cash flow distribution
in (1) can be enhanced from $H$ to $J$—each firm’s initial owners and manager know $r$, but
others do not. It is common knowledge that $r$ is distributed in the cross-section of sound
firms over \([r_a, r_b]\) according to the probability density function \(z\) (with associated cumulative distribution function \(Z\)).

The third information friction is that the firm’s manager may unobservably divert the funds \((R)\) raised for investing in R\&D at \(t = 2\) for personal benefit, rather than making the investment. Let the manager’s private benefit from doing so be \(\beta > 0\), and let the manager’s utility be defined as follows:

\[
U_M = c_1 V + c_2 \beta,
\]

(3)

where \(c_1 > 0, c_2 > 0\) are weights and \(V\) is the net present value (to the shareholders) from investing \(R\) at \(t = 2\). The probability is \(\kappa \in (0, 1)\) that the private benefit project will be available to the manager. Its availability is privately observed only by the manager. If the manager invests in this project, the probability that it will yield a positive cash flow is 0, but it will generate a private benefit of \(\beta\) for the manager. It is assumed that

\[
R > c_2 \beta > c_1 \left[ \delta \int_{x_L}^{\infty} x dH + [1 - \delta] \int_0^{x_L} x dL - R \right],
\]

(4)

which means that the private-benefit project is socially inefficient (produces a utility benefit of \(c_2 \beta\) for the manager, but requires an investment of \(R\) by the firm), but the manager will invest in the private-benefit project whenever it is available. An alternative interpretation of this private-benefit project is a project that is a “castle in the sky” for a researcher, which may have pure research value but little commercial value.\(^{14}\)

When the firm raises financing at \(t = 0\), it can decide how much information it wishes to disclose. Let \(\xi\), chosen from a compact set \([0, \xi_{\text{max}}]\), denote the extent of information disclosure. Information disclosure has two effects, one on the investors providing the financing, and the other on the firm’s potential competitors who may decide to jump in and invest in

\(^{14}\)The private benefit project can also be interpreted as managerial perquisites consumption in the context of the Jensen and Meckling (1976) model in the sense that the manager, instead of investing in R\&D, uses \(R\) to finance perquisite consumption that yields a utility of \(\beta\) to the manager (which could also be some form of quasi-rents that the manager is able to expropriate from the project). In fact, as Hellwig (2009) argues, thinking about perquisites consumption as another project is a more “symmetric” treatment of the agency costs of equity than the set-up in Jensen and Meckling (1976).
the same kind of R&D, thereby triggering an R&D “arms race” that will negatively impact the firm’s cash flow distribution. That is, the firm faces a “two-audience” signaling problem in its choice of disclosure.\footnote{As discussed in the introduction, while a firm may have to publicly disclose some aspects of its R&D through either patent filings, there will still be valuable private information about the future prospects of the R&D that the firm does not disclose. This problem would be particularly acute for the biopharma industry, as drug research is essentially winner-takes-all—the firm that successfully completes R&D and gets their drug approved through the FDA gets a monopoly on the drug through “exclusivity” marketing rights granted through the patent process, and can reap the very high cash flows that may come with such drugs.}

Since the amount of information disclosure $\xi$ pertains to the quality/profitability of the base R&D project, if it is available, it conveys no information about incremental value enhancement due to investing the additional $\Delta R$. That is, $\xi$ conveys no information about $r$. Let $\bar{r}$ be the expected value of $r$ to investors and other outsiders, i.e.,

$$\bar{r} = \int_{r_{a}}^{r_{b}} rzdr. \tag{5}$$

This is meant to capture the fact that while information disclosure may help to reduce some of the asymmetric information pertaining R&D projects, there are some aspects of R&D that the firm knows more about than the market, and its voluntary information disclosure is not able to lessen this information asymmetry. The effects of the disclosure $\xi$ on the firm’s R&D competitors and investors are described next.

### 3.3 The Effect of Information Disclosure

For investors, the effect of disclosure $\xi$ is to create a noisy but informative signal $\phi$ of the soundness of the firm which has the following probability distribution:

$$\Pr (\phi = \text{unsound} \mid \xi, \text{firm is unsound}) = p(\xi), \tag{6}$$

where $p' > 0$, $p'' < 0$, $\forall \xi \in [0, \xi_{\max}]$, and the Inada-type condition $p'(\xi_{\max}) = 0$ holds. This means that the precision of the investors’ signal that the firm is sound is positively related
to the amount of information disclosed by the firm. It is assumed that:

\[
\text{Pr} (\phi = \text{sound} \mid \xi = 0, \text{firm is sound}) = \text{Pr} (\phi = \text{sound} \mid \xi = 0, \text{firm is unsound}) = p(0) = \frac{1}{2}.
\] (7)

Let ˆs(ξ) be the posterior probability that investors have that the firm is sound, after it has disclosed ξ.

The effect of disclosure on competitors is as follows. Imagine, for simplicity, that the firm has only one competitor who may come in. If the firm discloses information about its R&D when it raises financing at \( t = 0 \), this competitor can update its belief about the value of entering the race. We assume that the more the firm discloses, the higher the probability of competitive entry, and that this entry will drive down the prospects of the firm being able to profitably continue to develop its R&D in the second stage starting at \( t = 2 \). This is modeled by assuming that a higher ξ leads to a higher probability of competitive entry, \( \theta(\xi) \in [0, 1] \), with \( \theta'(\xi) > 0 \) and \( \theta''(\xi) > 0 \). In addition, \( \theta(0) = 0 \), \( \theta(\xi_{\text{max}}) = \bar{\theta} \), and the Inada-type conditions hold: \( \theta'(0) = \infty \) and \( \theta'(\xi_{\text{max}}) = 0 \). If there is no competitive entry due to information disclosure, the probability of a good first-stage R&D outcome for the firm is \( q = \bar{q} \) and if there is competitive entry it is \( q = \bar{q} \), with \( 0 < \bar{q} < \bar{q} < 1 \). We will assume that \( \bar{q} > 2\bar{q} \).

3.4 The Firm’s Second-Stage Investment Decision

We will assume that it will be worthwhile for the firm to invest \( R \) at \( t = 2 \) only if it receives the signal that tells it that its first-period R&D yielded good results (G). If it receives the signal and learns that the first-period R&D yielded bad results, then it has no incentive to invest \( R \) at \( t = 2 \) since the payoff from doing so is 0. We further make the following

\[\text{This is a minor technical condition used in the proof of Proposition 2, which ensures that competitive entry has a significant impact on the first-stage probability of success.}\]
assumptions:

\[ q \bar{G} < R, \quad (8) \]

\[ \omega R < q \left[ \bar{G} - R \right], \quad (9) \]

where \( \bar{G} \equiv \delta \int xdH + [1 - \delta] \int xdL > \delta \left[ \int xdH - \int xdL \right] > R \). Condition (8) says that absent the signal at \( t = 1 \) about the outcome of the first-stage R&D, the firm will choose not to invest \( R \) in the second stage. Condition (9) says that the expected value of the option to invest \( R \) in R&D in the second stage exceeds the investment \( \omega R \) in R&D in the first stage for any value of \( q \).

3.5 The Moral Hazard Problem in the Second-Stage

The moral hazard problem at \( t = 2 \) is that the manager may have an opportunity to misuse the capital \( R \) at his disposal in order to pursue a private benefit without this being directly and costlessly observable. If the firm has used debt financing, bondholders can use it as a monitoring signal to determine whether the manager is investing \( R \) in further R&D or appropriating it for the private-benefit project. If their signal reveals that the manager is pursuing private benefits, they can stop the project, recover the investment of \( R \) and ask to be repaid at \( t = 2 \). We assume irreversibility of investment in the sense that once the manager invests in the private-benefit project, the bondholders can stop it to recover \( R \) at \( t = 2 \), but the firm cannot go back to the R&D project.

The use of debt as a monitoring/disciplining device to prevent misappropriation of resources by managers has has been extensively discussed in the literature (e.g. Hart and Moore (1995, 1998) and Jensen (1986), among others). However, we operationalize this in a novel way by making the effectiveness of the monitoring device dependent on the characteristics of the firm’s projects. More specifically, the monitoring technology produces a signal \( y \) to determine the probability of (monetary) success of the investment. If there are two projects with probabilities of achieving success (defined as the probability of the date-3...
cash flow being drawn from the distribution $H$) given by $y_1 \in [0, 1]$ and $y_2 \in [0, 1]$, then the probability distribution of the signal $y \in \{y_1, y_2\}$ identifies which project has been selected:

$$
\Pr(y = y_i \mid y_i) = 0.5 + \frac{|y_i - y_j|}{2},
$$

where $i \neq j$ and $i, j \in \{1, 2\}$. That is, the precision of the signal (the probability with which it correctly identifies the project) is higher the more different the projects are from each other in terms of their success probabilities. The idea is that the more similar the projects are to each other, the harder it is to tell them apart. Thus, for good projects with low probabilities of success, bondholders have difficulty differentiating those projects from private benefit projects.

Finally, another reason why the bondholders may find it difficult to distinguish between good R&D projects and the pursuit of private benefits is the highly technical and specialized nature of R&D that is typically pursued by biopharma and other R&D-intensive firms. The firm’s manager has a large technical expertise advantage over financiers in addition to privileged access to localized private information.

### 3.6 The Effect of Competitive Entry due to Information Disclosure in the Second-Stage

Competitive entry has two effects on the profitability of R&D. First, if a competitor enters at $t = 0$ and also invests $\omega R$, then the first-stage R&D will yield a good outcome (success) with probability $q$. Since competitive entry at $t = 0$ reduces the probability of R&D success to $\frac{1}{2}$ for both firms, the two firms’ first-stage R&D outcomes are perfectly correlated. Second, if both firms are competing, then even conditional on a good first-period R&D outcome, the second-period R&D is less profitable. This is captured by assuming that the payoff distribution $H$ vanishes and each firm’s cash flow is driven with probability 1 by the distribution $L$, i.e., the NPV of the investment at $t = 2$ becomes $\varepsilon > 0$. 

19
Note that even if the competitor who enters at \( t = 0 \) does not make the investment \( R \) at \( t = 2 \), if it becomes publicly known that the firm achieved good results on its first-stage R&D, then any new competitor can come in at \( t = 2 \) and invest \( R \) in second-stage R&D.\(^{17}\) Recall that there is an \( \varepsilon > 0 \) profit for any firm that does this, so there is an incentive for it to do so.

The assumption that higher competition has such a two-fold effect on R&D is a reasonable approximation of reality. On the one hand, competition creates an initial arms race between competing firms, which means that both are competing for and dividing up the available pool of human talent for the R&D and also suppliers who may come up with innovations in inputs. Hence, \( q \) becomes lower. On the other hand, even if there is first-period R&D success, competition also has an adverse effect on second-period profits.

### 3.7 Discussion of the Setup of the Model

*Figure 2* summarizes the timeline of events. Note that formally this is a game in which the informed firm moves first with its financing and information disclosure decisions, and the uninformed investors move next. As *Figure 2* indicates, this model is rich, with many elements. We briefly summarize here the role these elements play in the model and how they correspond to biopharma firms in practice.

The first set of elements has to do with the sequential staged nature of R&D and escalating resource commitments over time. In our model, as in practice, there is an initial exploratory investment in R&D, followed by a subsequent (larger) investment if the initial R&D yields promising results. This is captured by an investment of \( \omega R \) at \( t = 1 \) and then a possible additional investment of \( R \) at \( t = 2 \), that is conditional on good (\( G \)) first-stage R&D results.

The second set of elements has to do with the pros and cons of information disclosure

---

\(^{17}\)For example, the successful completion of research on the human genome project in the 1990s and 2000s—the results of which were publicly released—allowed a proliferation of biotech companies in the marketplace (see Thakor et al. (2015)). As another example, after the Hatch-Waxman bill of 1984 was passed for the biopharma industry, it became easier for generics to enter the marketplace by skipping initial trials if someone had previously proven efficacy.
<table>
<thead>
<tr>
<th>$t = 0$</th>
<th>$t = 1$</th>
<th>$t = 2$</th>
<th>$t = 3$</th>
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| • Sound firm needs $\omega R$ for initial R&D investment and $R$ for later investment.  
• Firm raises financing from debt, equity, or a mix  
• The firm’s initial owners (insiders) could also liquidate personal assets $\Lambda$ at a cost as an alternative to capital market financing.  
• Probability is $s \in (0, 1)$ that the firm is sound and $1 - s$ that it is unsound.  
• The firm chooses how much information $\xi$ to disclose. This affects investors’ posterior beliefs that firm is sound as well as probability $\theta$ of competitive entry. | • Manager decides whether to invest $\omega R$ in an R&D project (if there is a worthwhile one).  
• If the firm invested at $t = 1$, then with probability $q$ the investment yields $G$ (good results), and with probability $1 - q$ that it yields $B$ (bad results).  
• $q = \bar{q}$ with no competitive entry, and $q < \bar{q}$ with competitive entry.  
• The firm may raise additional financing from debt, equity, or a mix  
• With $G$, firm invests $R$ at $t = 1$. May also invest additional $\Delta R$.  
• With $B$, firm ceases further investment.  
• If the manager receives a private-benefit project, he invests $R$ in it, unless bondholders detect and stop it. | • Final R&D payoff $x$ is observed.  
• If firm invested $R$ at $t = 2$, then $x \sim H$ with probability $\delta$ and $x \sim L$ with probability $1 - \delta$.  
• If firm also invested additional $\Delta R$ at $t = 2$, then high cash-flow realization (which happens with probability $\delta$) becomes $x \sim J$ with probability $r$, or remains $x \sim H$ with probability $1 - r$.  
• Investors are paid off. |  

*Figure 2: Time-line of Events and Decisions*
about the R&D. In practice, as in our model, the benefit of information disclosure is a reduction in the adverse-selection of external financing, which is captured by introducing a non-zero probability \((1 - s)\) of investors encountering an unsound firm. The cost is that the more information the firm discloses, the higher is the probability \(\theta\) that a competitor will enter and reduce the expected value of R&D to the firm. However, information disclosure pertains to only one aspect of R&D, leaving one informational asymmetry entirely unresolved.

The third set of elements has to do with informational frictions. The probability \(s\) of a firm being sound is introduced to capture adverse selection in external financing, which is a well-known friction. The ability to undertake a value-enhancing R&D investment \(\Delta R\) provides the opportunity for the firm to widen the commercial applicability of the project, while the probability \(r\) of finding a worthwhile R&D-enhancing project is introduced to capture the idea that market financing may be incapable of resolving all informational problems. This leaves some room for mechanism design to play an incremental role, something we explore later in the paper. The private-benefit project for the manager introduces moral hazard and creates a positive role for debt as a monitoring device, but also creates a cost in the sense that it becomes difficult for bondholders to distinguish between private-benefit projects and legitimate projects (with low probabilities of success). Thus, the analysis depends on second-stage R&D success having a sufficiently low probability \((\delta)\). This captures an essential feature of biopharma R&D (compared to other forms of R&D) that it has very low success probabilities and high payoffs conditional on success.

We assume throughout that the deadweight cost of liquidating personal assets makes it prohibitively expensive for insiders to raise all of the financing through personal-asset liquidation.
4 Analysis

We now analyze the model. The initial owners of the firm decide at $t = 0$: (1) how much financing to raise; (2) whether to raise financing with a mix of debt and equity, just debt, or just equity; and (3) how much information to disclose. For now, we will ignore the self-financing option for the initial owners, and verify later that there are conditions under which self-financing is not optimal.

The manager runs the R&D project. At $t = 1$, the manager will decide whether to invest $\omega R$ in initial R&D. At $t = 2$, he will have to determine whether to invest $R$ for further R&D or invest undetectably in the private-benefit project (if it is available). The manager makes this decision to maximize his expected utility.

4.1 Analysis of Financing, Disclosure, and Investment Decisions

Our first result is about how much financing the firm will raise at $t = 0$.

Proposition 1: The firm will raise all of the financing it needs, $[1 + \omega] R$, at $t = 0$. It will invest $\omega R$ in its first-stage R&D at $t = 1$ and carry a cash stockpile of $R$ to date $t = 2$.

The intuition behind this result is that the firm will not want to raise additional capital at $t = 2$ because doing so would signal project success not only to the market, but also to its competitors. Competitive entry at that point in time would reduce the margins of the project—something the firm would like to avoid. Thus, the firm will optimally want to raise all of its necessary capital earlier, when it knows less about the potential success of the R&D project.

Disclosure at $t = 0$ is “partial” and only increases the probability of competitive entry, $\theta$, thereby reducing the probability of a good R&D outcome at $t = 1$. But raising capital at $t = 2$ is tantamount to “full” disclosure about the value of the R&D (since it unambiguously reveals first-period R&D success), so it induces competitive entry with certainty, driving

\footnote{Proofs are provided in the Appendix.}
down profits. Thus, it is rational for the firm to disclose information at $t = 0$, before it knows how the first-period R&D will fare. In other words, it makes sense to raise considerable external financing when the firm knows less and then use it as an internal capital market to fund additional R&D when it knows more.

Next we consider whether the firm will use debt or equity to raise financing at $t = 0$. Consider first equity. The firm now has to choose how much information to disclose. Let $f$ be the fraction of ownership that the initial owners sell to investors of the sound firm in order to raise $[1 + \omega] R$. That is, assume initially that $\Delta R$ is not raised. The initial owners of the sound firm solve the following maximization problem:

$$
\max_{\xi \in [0, \xi_{\text{max}}]} [1 - f] \Omega (\xi),
$$

subject to:

$$
\hat{s} (\xi) f [\Omega (\xi)] = [1 + \omega] R,
$$

and

$$
\Omega (\xi) \equiv [1 - \kappa] \left\{ \bar{q} [1 - \theta (\xi)] \bar{G} + [1 - \bar{q}] [1 - \theta (\xi)] R + q \theta (\xi) \int_{0}^{x_L} x dL + [1 - q] \theta (\xi) R \right\},
$$

This maximization can be understood as follows. (11) is given by the initial owners maximizing their share of the total firm value $\Omega (\xi)$, when their post-financing ownership share is reduced to $[1 - f]$. Equation (12) is the outside investors’ equilibrium pricing constraint, where $\hat{s} (\xi)$ is the investors’ posterior belief that the firm is sound after the disclosure $\xi$ has occurred. Finally, (13) is the total firm value. If no competitive entry occurs (probability $1 - \theta (\xi)$), then the probability of success of the first-stage R&D is $\bar{q}$. Then, conditional on first-stage success, the second-stage R&D generates a firm value of $\bar{G}$. If the first-stage R&D
does not succeed (probability $1 - \bar{q}$), cash $R$ sits idle. This explains the first two term in the braces in (13). For the third term, if competitive entry occurs (probability $\theta(\xi)$), then the first-stage R&D success probability drops to $q$, and the firm’s value is $\int xdL$. Finally, in this case with competitive entry (probability $\theta(\xi)$), if the first-stage R&D does not succeed (probability $1 - q$), cash $R$ sits idle. This explains the fourth term in the braces in (13). The sum of the terms in the braces is multiplied with $1 - \kappa$, the probability that the manager will not divert $R$ for the private-benefit project.

The next result connects the amount of information disclosure firms choose to the equity financing that they are able to secure:

**Lemma 1:** Conditional on the firm being sound, a higher $\xi$ leads to a higher posterior probability, $\hat{s}(\xi)$, that the firm is sound.

The intuition is that a higher amount of disclosure $\xi$ leads to a higher precision of the signal investors receive about the firm’s type, so the posterior belief that a firm is sound is higher for a sound firm when $\xi$ is higher. Holding fixed the value of the firm, this means that a greater amount of disclosure leads equity investors to demand a lower fraction of ownership $f$ in exchange for the funding that they provide (see (12)). As firm value declines as $\xi$ increases (due to the damaging effects of competitive entry), this creates a tradeoff that enables us to establish an optimal level of information disclosure with all-equity financing:

**Proposition 2:** Assuming only equity financing and that no firm wants to invest $\Delta R$, there exists a unique interior optimal level of disclosure $\xi^*$ that solves the problem in (11)–(14).

This proposition states that firms will choose a level of $\xi$ that trades off the costs and benefits of disclosure. On the one hand, greater disclosure leads to a higher posterior belief among investors that the firm is sound as $\partial \hat{s} / \partial \xi > 0$ (see Lemma 1). On the other hand, a higher $\xi$ also increases the probability of competitive entry, $\theta$, which reduces the value of R&D to the firm. An interior optimum is achieved that balances the benefit of a lower cost of financing against the cost due to a higher probability of competitive entry. This interior
optimum also implies that firms have no incentive to disclose further information beyond $\xi^*$ for signaling purposes.

Let us now consider the firm’s incentive to raise the financing $\Delta R$. We assume that, evaluated at $\bar{r}$, the prior belief about $r$, the payoff-enhancement R&D investment has negative NPV, i.e.,

$$
\bar{q}\delta \left[ \bar{r} [\mu_J - \mu_H] \right] < \Delta R,
$$

(15)

where

$$
\mu_J = \int_{x_H}^{x_J} xdJ, \tag{16}
$$

and

$$
\mu_H = \int_{x_L}^{x_H} xdH. \tag{17}
$$

The next result establishes a pooling sequential equilibrium with respect to the R&D-enhancing investment, $\Delta R$.

**Proposition 3:** There exists a sequential equilibrium where all firms avoid raising financing $\Delta R$ for R&D payoff enhancement. If a firm chooses to raise this financing, investors believe it is unsound with probability 1.

The intuition is that raising financing for a project that on average is negative NPV is most attractive for the unsound firms. The market understands this and as a result will identify a firm as unsound if it tries to raise financing for the R&D enhancement. In equilibrium, no firm will therefore choose to undertake the R&D enhancement using market financing.\(^19\)

Consider now debt financing. Let $F$ be the face value of the debt that must be repaid at $t = 3$. However, if bondholders wish to demand early repayment at $t = 2$, they can do so if they can show that the manager has chosen to invest in the private-benefit project. Let $\Omega_D (\xi)$ be the firm value with debt.

\(^{19}\)With reasonable additional parametric restrictions, we could establish that this equilibrium survives refinements of sequential equilibrium.
Note first that (10) now becomes:

$$\Pr (y = \delta \mid \delta) = 0.5 + \frac{\delta}{2} = \frac{1 + \delta}{2}, \quad (18)$$

and

$$\Pr (y = 0 \mid \delta) = \Pr (y = \delta \mid 0) = 1 - \frac{1 + \delta}{2} = \frac{1 - \delta}{2}. \quad (19)$$

Clearly, $\Pr (y = 0 \mid \delta)$ is decreasing in $\delta$.

Now, if we designate $\mathbb{E} [F \mid r]$ as the expected value of the bondholders’ repayment for $r = \overline{r}$ when $F$ is the face value of debt and the firm is sound, then to obtain the disclosure level that maximizes the expected value of the initial owners’ payoff, with the expectation taken over $[r_a, r_b]$, we solve:

$$\max_{\xi \in [0, \xi_{\text{max}}]} \Omega_D (\xi) - \mathbb{E} [F] \quad (20)$$

subject to

$$\hat{s} (\xi) \mathbb{E} [F] = [1 + \omega] R, \quad (21)$$

$$\Omega_D (\xi) = [1 - \theta (\xi)] A_2 + \theta (\xi) A_3, \quad (22)$$

where

$$A_2 \equiv \kappa \{\Pr (y = \delta \mid 0) [0] + \Pr (y = 0 \mid 0) R\}$$

$$+ [1 - \kappa] \left\{\bar{q} \{\Pr (y = \delta \mid \delta) G + \Pr (y = 0 \mid \delta) R\} + [1 - \bar{q}] R\right\}, \quad (23)$$

$$A_3 \equiv \kappa \{\Pr (y = 0 \mid \delta) R + \Pr (y = \delta \mid 0) [0]\}$$

$$+ [1 - \kappa] \left\{q \{\Pr (y = 0 \mid \delta) R + \Pr (y = \delta \mid \delta) [R + \varepsilon]\} + [1 - q] R\right\}. \quad (24)$$

This maximization program can be understood as follows. The wealth of the sound firm’s initial shareholders is the total value of the firm minus what the firm owes in expectation to
the bondholders—this is given by (20). What the firm owes to the bondholders is determined by the competitive equilibrium pricing constraint (21), and it includes the posterior belief $\hat{s}(\xi)$ that the firm is sound. The total firm value is defined in (22). It is the sum of two parts. The first part, $A_2$, pertains to the value if there is no competitive entry, and the probability of success in this case is $\bar{q}$. The probability of no competitive entry is $1 - \theta(\xi)$. The second part, $A_3$, pertains to the value if there is competitive entry, and the probability of success in this case is $q$. The probability of competitive entry is $\theta(\xi)$.

Now consider $A_2$. With probability $\kappa$, the manager will have a private-benefit project available, in which case there are two possibilities. One is that the bondholders will correctly identify that the manager has chosen such a project and put a stop to it, saving the investment $R$. The probability of this is $\Pr(y = 0 \mid 0)$. The other possibility is that bondholders fail to recognize that the manager is investing in the private-benefit project and thus fail to stop it (probability $\Pr(y = \delta \mid 0)$). In this case, firm value is 0. With probability $1 - \kappa$, the manager does not have a private-benefit project. In this case, if the bondholders correctly recognize this (probability $\Pr(y = \delta \mid \delta)$), they allow the manager to proceed with the legitimate R&D investment, and firm value is $G$. If the bondholders erroneously think that the manager has invested in the private-benefit project (probability $\Pr(y = 0 \mid \delta)$), they stop the investment and firm value is $R$.

Next consider $A_3$. With probability $\kappa$, the manager invests in the private-benefit project and the payoffs are the same as with $A_1$. With probability $1 - \kappa$, the manager will not invest in the private-benefit project. If the bondholders mistakenly shut down the R&D project (probability $\Pr(y = 0 \mid \delta)$), firm value is $R$. If the bondholders correctly identify the firm’s project (probability $\Pr(y = \delta \mid \delta)$), then the firm value is $\int x dL = R + \varepsilon$.

The next result states that, with debt financing in addition to equity financing, there is also a unique level of disclosure chosen by the firm:

**Proposition 4:** There exists a unique interior optimal level of disclosure $\xi^\circ \in \left[0, \xi_{max}\right]$ chosen by the firm’s initial owners.
4.2 Analysis of Optimal Capital Structure

We now examine the firm’s choice of debt versus equity at $t = 0$. Recall that $\mu_H \equiv \int x dH$, and define $\mu_L \equiv \int x dL$.

**Proposition 5:** For a given value of second-stage R&D, equity is strictly preferred to debt at $t = 0$ if the moral hazard problem is not too severe (i.e., if $\kappa$ is low enough). For a given level of moral hazard (a given $\kappa$), equity is strictly preferred to debt if the “upside” value of R&D, as represented by $\mu_H$, is large enough. Moreover, for any given $\mu_H$ and $\kappa$, the value of equity relative to debt is decreasing in $\delta$, the probability of the upside value of the R&D. For $\mu_H$ large enough and $\kappa$ small enough, $\xi^0 > \xi^*$.

This proposition shows that equity will strictly dominate debt when conditions that typically exist in biopharma firms are encountered. These conditions are: R&D with low probabilities of success (low $\delta$—note that a preference for equity gets stronger as $\delta$ declines) but a high upside potential (high $\mu_H$), and low moral hazard (likelihood that R&D will be abandoned in favor of unproductive private-benefit projects). The intuition for why a low probability of R&D upside favors equity relative to debt is as follows. As the probability of R&D success declines, it becomes more difficult for bondholders to distinguish between legitimate R&D and a private-benefit project, both of which look like long-shots to produce any monetary value for the firm. This reduces the value of debt relative to equity. Similarly, a high upside potential for the R&D makes an error on the part of the bondholders more costly to the firm, thus further reducing the value of debt relative to equity. Finally, low moral hazard is necessary because debt is a valuable disciplining device—thus if moral hazard were high, the value of debt relative to equity may be high.

The last part of the proposition says that the firm discloses less information with equity than with debt. The reason is that, for a given increase in information disclosure, equity provides a larger “bang for the buck” than debt in terms of affecting the amount of capital that investors are willing to provide. This intuition is also consistent with papers that have
argued that debt is less informationally sensitive than equity (e.g. Townsend (1979), Dang, Gorton, Holmstrom (2012), and Holmstrom (2015)). This allows the firm to optimally disclose less information with equity, and hence less firm value is lost due to information disclosure with equity than with debt.\textsuperscript{20}

4.3 Model Discussion and Extensions

In this section, we discuss a number of possible extensions of the model related to how biopharma firms operate in the real world, and how these may affect the conclusions of the previous section.

4.3.1 Tangible Assets-in-place or Cash Reserves

In our analysis, we assume that the firm has no significant assets-in-place or cash reserves at the beginning $t = 0$. However, in practice many large R&D-intensive firms have large cash stockpiles or assets-in-place. If the firm has cash or tangible assets-in-place at $t = 0$ that could be used to repay debt, then debt could become the optimal security for two reasons.

The first reason is that, assuming that the firm either has cash reserves or a low cost of liquidating assets, the firm could use the cash/assets to repay bondholders at $t = 1$ if they erroneously demand a stop to the project. This could enable the firm to have the bondholders stop monitoring the project, and still invest in second-stage R&D. Moreover, to the extent that the firm’s owners can tell when bondholders are incorrect with their signal, the firm may still be able to use debt as a monitoring device. Thus, with cash or assets-in-place, debt may be optimal by maintaining its monitoring advantage without the cost associated with it.

\textsuperscript{20}This can be seen by considering equity to be a long call option on the value of assets of the firm, while debt is a combination of a short put option and a riskfree bond. The strike price in both cases is the outstanding face value of debt. Note that changes in information disclosure will change the value of the firm. Since the gamma of a long call option is positive, the delta of the call (which can be interpreted as the sensitivity of the option with respect to information disclosure) will increase as firm value increases. Since the gamma of a short put option is negative, the delta of the short put will decrease as firm value increases. Thus, for sufficiently large firm values, the delta of the short put option will be less than the delta of the long call option. Condition (7), combined with a high upside value of R&D, ensure this.
The second reason why debt may become optimal is that cash or assets-in-place may serve as collateral to substitute for information disclosure. The promised repayment of debt is a fixed claim, and with assets securing the claim, there is less need for information disclosure when raising debt. While the optimal level of information disclosure in the previous analysis was higher with debt than with equity, a sufficiently large amount of cash or assets-in-place may reduce the amount of information disclosure for debt to a level below that for equity, thus making debt optimal. Alternatively, this could also allow the firm to issue more equity and debt at \( t = 0 \) than needed to finance both stages of R&D, and keep excess cash as a precautionary stockpile to pay off debt early (at \( t = 1 \)) if necessary, without disrupting its second-stage R&D investment.

Overall, this means that if the biopharma firm has significant tangible assets or cash reserves ex ante, it may use some debt. But in that case, the amount of excess cash it will carry will be even higher than predicted by the analysis here. That is, (gross) debt may be non-trivial, but net debt (net of cash) may still be low. This is consistent with the empirical evidence provided by Thakor and Lo (2015).

This extension in the analysis may provide a differentiation among R&D-intensive firms, for example between pharmaceutical (“pharma”) and biotechnology (“biotech”) firms, in terms of their capital structure. Pharma firms tend to have greater amounts of assets-in-place (as well as larger cash reserves) than biotech firms, as a result of existing product lines and drug manufacturing operations. The theory therefore predicts that pharma firms will optimally tend to have more debt in their capital structure than biotech firms, a fact that holds empirically (see Thakor et al. (2015)).

4.3.2 Portfolio of Projects

While we present the R&D project in our model as a single project, in practice it could also be considered as a reduced-form representation of a portfolio of projects. For example, an R&D-intensive firm like a large pharmaceutical company will typically make simultaneous
investments in portfolios of R&D projects. In this setting, a portfolio of projects may provide a number of benefits. One benefit is risk diversification for the firm—this has also been emphasized in the context of a drug “megafund” by Fagnan et al. (2013) and Fernandez et al. (2012). Related to this benefit of diversification, a portfolio also allows for an improvement in the signal-to-noise ratio of the projects for the signal produced by the bondholders in this model, as the idiosyncratic “noise” is diversified away through a portfolio of projects. This allows an improvement in the quality of their monitoring, which in turn reduces the chance that they erroneously stop the R&D project before completion—this may allow the firm to support more equity or debt in its capital structure. Finally, another benefit of a portfolio of projects may be a lower per-project cost of disclosing proprietary information to product-market competitors. This is because, since the idiosyncratic nature of each project is diversified away through the portfolio, the technical aspects of each individual R&D project are also obscured to competitors, thus revealing less information about any one project.

4.3.3 Debt Signaling

The results in the previous sections establish a financing pecking order, but there is also a pooling equilibrium where all firms do not invest in the (socially) valuable R&D-enhancement, $\Delta R$. A natural question that arises is whether it is possible to avoid this pooling outcome through signaling? Ross (1977) first introduced the idea that the amount of debt financing used by a firm could act as a signal of its value when the manager is privately informed about this value. Given this, could the firm raise debt at $t = 0$ to signal its privately-known value of $r$, thus allowing some firms to invest in the R&D-enhancement?

In the setting of our model, debt signaling does not work to eliminate the pooling with respect to the R&D-enhancing investment. To see why, note that for debt to be a signal as in Ross (1977), the single-crossing property must be satisfied and the marginal cost of signaling should be lower for the firms with higher values of $r$. However, the marginal cost of using debt in our model to separate sound firms with different values of $r$ is the same
for all values of $r$ since it stems from the probability that the bondholders will erroneously terminate a good project.\footnote{Note that if debt signaling were feasible, the unsound firm would always wish to mimic the sound firm with the highest $r$ in order to raise the maximum financing at $t = 0$.} This means that the single-crossing property will not hold, and a separating equilibrium will not arise. In the subsequent analysis, we explore a possible resolution to the pooling outcome of the R&D-enhancement.

### 4.3.4 Convertible Bonds

In the previous analysis, we have just considered straight equity and debt as choices of securities that the firm may issue. However, in practice firms use other types of instruments as well. For example, one of the most common forms of public market funding used by biopharma firms is convertible debt. It is therefore interesting to consider whether convertible debt is an optimal method of funding when compared to straight debt or equity within the context of our model.

Functionally, convertible debt acts as normal debt with an added option for the holder of the debt to convert the claim into equity. Alternatively, convertible debt may be callable—issued so that the issuing company has the option to convert it early into equity when it sees fit. The optimality of convertible debt in our framework therefore depends on which type of convertible debt is issued.

First consider the case where the holder has the option to convert the debt into equity. Assuming that convertible debt-holders have monitoring capability similar to that of straight debt holders, they will choose (perhaps erroneously) to shut down a project that they view as a private benefit project. Therefore, convertible debt shares the same cost as straight debt in our model, namely the possibility of shutting down a good project. However, if the project succeeds at $t = 3$, then the holder will choose to convert the security into equity—this option will be initially priced into the convertible as a lower coupon rate/face value. Moreover, given that the optimal level of information disclosure $\xi$ is lower for equity than for debt, the conversion feature of convertible debt also implies that the optimal level of
information disclosure for convertible debt will be between that of debt and equity. Since overall firm value is decreasing in the amount of information disclosure, this in turn implies that convertible debt in this setting will be preferrable to straight debt, but less attractive than equity.

Next consider the case where the convertible debt is callable, so the firm has the ability to convert the security into equity. If the firm is confronted with the prospect of a bondholder-initiated project liquidation, it may convert the debt into equity to forestall the liquidation. This is beneficial for the shareholders when the bondholders have erroneously identified a good R&D project as a private-benefit project. However, note that the manager will have an incentive to call the convertible to avoid liquidation even when the private benefit project has been chosen. So the convertible loses all of the potential discipline of debt, and it can be viewed as a type of “backdoor” equity (as in Stein (1992)).

In reality, convertible debt covenants create securities that are hybrids of the two cases we consider above. However, this discussion indicates that, at best, convertible debt is equivalent to equity in terms of the biopharma pecking order. In other cases, it will be in between debt and equity in the pecking order. It should be noted that convertible debt, like debt and equity, will not solve the problem of non-investment in the R&D-enhancement $\Delta R$. Indeed, to the extent that it is not possible to contract on (or reveal) the probability of success $r$ of the R&D-enhancement, then any other alternative security will also not be able to solve this underinvestment problem. We solve this problem through a mechanism design, which we discuss next.

4.3.5 Tax Implications for Multinationals

There is one institutional feature of multinational firms that we have not captured in our framework and which has a direct impact on the preference between equity and debt: taxes. Apart from the usual interest-deductibility incentive for debt financing, there is an additional incentive for U.S.-domiciled multinationals to take on debt that stems from their ability to
avoid paying taxes on foreign earnings that have not been repatriated.\textsuperscript{22} Firms with large amounts of accumulated foreign cash often access these resources by issuing debt, which has no material impact on the firm’s credit rating as long as the debt burden does not exceed the after-tax value of the foreign reserves. As a result, certain multinational pharma companies may seem to be highly leveraged at first blush, but when foreign cash reserves are netted out, their leverage ratio is considerably lower.

5 An Exploration of a New Financing Mechanism Design

The previous analysis assumed that firms would rely on standard debt and equity contracts to finance R&D, and proceeded to derive a pecking order in which equity ends up at the top. However, there is still a friction that is not resolved by market financing—no firm will choose to invest $\Delta R$ to enhance the R&D payoff distribution from $H$ to $J$, even though such an investment would be valuable for some firms.\textsuperscript{23} This raises the question of whether there is a mechanism beyond straight market financing that may improve outcomes, and allow this R&D enhancement to be undertaken.

To explore this, we introduce a hypothetical “arbitrator” who can, unlike the pure market financing case, make binding precommitments and get firms to do the same. That is, armed with precommitment and not constrained to debt and equity, we examine whether an arbitrator can design a financing mechanism that improves the expected net payoff of firms.

\textsuperscript{22}See Foley, Hartzell, Titman, and Twite (2007) and Hanlon, Lester, and Verdi (2015) for a discussion of the effect of the repatriation tax on earnings and cash.

\textsuperscript{23}One could also interpret this enhancement as something that has a positive social externality that is not internalized in the NPV calculation for the firms. For example, this could be some sort of drug that may have wider applications given further testing.
5.1 Mechanism Design Framework

We approach this in a standard mechanism-design framework (e.g. see Myerson (1979)). The arbitrator asks each firm to directly and truthfully report its $r$ to the arbitrator at $t = 0$. Based on the report, the arbitrator asks the firm to sell to the equity investors it raises financing from a put option with a strike price of $\zeta (r)$ and also attach to it a digital option that switches on and off according to the realized value of $x$. Specifically, the digital option makes investors long in the put and the firm’s insiders short in the put when $x \in [x_L, x_H]$, and insiders long in the put and investors short in the put when $x < x_L$. We will see that the strike price $\zeta \in (x_L, x_H)$. This means that when $x \in [x_L, x_H]$, investors exercise their put option and receive $\zeta - x$. When $x < x_L$, the insiders exercise their put option and receive $\zeta - x$. Figure 3 depicts the payoffs of these options from the perspectives of both the insiders and investors.

Note that when investors exercise their put option, the firm does not generate sufficient cash flow to satisfy their claim. Thus, the insiders of the firm must liquidate their personal assets $\Lambda$ at a cost. This requires a precommitment to the arbitrator’s scheme, something that is not available with market financing. Absent such precommitment, the firm’s insiders would simply invoke the firm’s limited liability and not sell personal assets at a cost to settle any payment on the put option. The scheme would then unravel.

Since the firm’s report $r$ is made at $t = 0$ (and we assume it becomes common knowledge right away), and it is always truthful in equilibrium in an incentive compatible mechanism, the firm can choose its disclosure after having reported its $r$. In other words, the firm can choose $\xi$ as if there was perfect (symmetric) information about $r$.

Let $\pi (r)$ be the probability that the arbitrator will allow the firm to participate in the scheme. If the firm is not allowed to participate, it must seek market financing, as in the previous section. Let $\alpha (r)$ be the social value the arbitrator attaches to the expected payoff due to the incremental investment $\Delta R$. Thus, the arbitrator’s mechanism $\Psi$ can be described.
Figure 3: Mechanism Payoffs

The left figure depicts the payoffs to the insider, while the right figure depicts the payoffs to investors. In the region where $x < x_L$, insiders are long in the put and investors are short in the put. In the region where $x \in [x_L, \zeta(r)]$, the insiders are short in the put and the investors are long in the put. In the region where $x > \zeta(r)$, the put is out of the money and the payoff is zero.
as:

$$\Psi : [r_a, r_b] \rightarrow \mathbb{R}_+ \times [0, 1].$$  \hspace{1cm} (25)

That is, the firm reports \( r \in [r_a, r_b] \) to the arbitrator, it is asked to create a put option strike price of \( \zeta (r) \in \mathbb{R}_+ \) (the positive real line), and is allowed to participate in the scheme with a probability of \( \pi (r) \in [0, 1] \). The firm then chooses its disclosure \( \xi \) and investors then determine the fractional ownership \( f \) that the firm must sell in order to raise \([1 + \omega + \triangle] R\) at \( t = 0 \). We rely on the result of the previous section that equity dominates debt in the external financing pecking order.

Let \( U (\tilde{r} | r) \) be the expected utility or net payoff of a firm whose true parameter is \( r \) but which reports \( \tilde{r} \). Before stating the arbitrator’s problem, we describe the first-best solution when each firm’s \( r \) is common knowledge. Because of the deadweight loss associated with insiders liquidating their own assets to cover the cost of the put option, in the first-best case no firm writes a put option. Each firm’s insiders maximize:

$$[1 - f] \Omega (r, \xi),$$

subject to\(^{24}\)

$$\Omega (r, \xi) = [1 - \kappa] \{ B_1 (\xi) \left[ G + \delta r [\mu_J - \mu_H] + B_2 \mu_L + B_3 R \right] \},$$

$$\hat{s}(\xi) f \Omega (r, \xi) = [1 + \omega + \triangle] R.$$  \hspace{1cm} (28)

In the above, note that

$$B_1 \equiv q [1 - \theta],$$

\(^{24}\)To obtain (27) below, note that

$$\Omega (r, \xi) = B_1 \left[ \delta \left( r \int_{x_H}^{x_J} x dJ + [1 - r] \int_{x_L}^{x_H} x dH \right) + [1 - \delta] \int_0^{x_L} x dL \right] + B_2 \int_0^{x_L} x dL + B_3 R$$

and substitute \( \mu_J = \int_{x_H}^{x_J} x dJ, \mu_H = \int_{x_L}^{x_H} x dH, \mu_L = \int_0^{x_L} x dL, \) and \( G \equiv \delta \mu_H + [1 - \delta] \mu_L. \)
\[ B_2 \equiv q \theta, \]  
\[ B_3 \equiv [1 - \theta] [1 - \bar{q}] + \theta [1 - q]. \]

### 5.2 Analysis of the Mechanism

We start by characterizing the first-best level of information disclosure, \( \xi \).

**Lemma 2:** There is a unique optimal level of disclosure in the first-best case that is strictly decreasing in \( r \).

Our next result shows that the arbitrator cannot implement the first-best solution when there is asymmetric information about \( r \).

**Lemma 3:** The first-best solution is not incentive compatible.

The reason why the first-best solution is not incentive compatible is that a firm with a higher \( r \) is more valuable holding fixed its disclosure level \( \xi \), and moreover, it also discloses less in the first best, further enhancing its value. Thus, there is a “double advantage” for the firm to masquerade as a firm with a higher \( r \)—it can “get away” with disclosing less and raising the needed financing by giving up a lower ownership share.

Under asymmetric information, the arbitrator’s problem can be expressed as that of designing functions \( \pi [0, 1] \) and \( \zeta \) to solve:

\[
\max \int_{r_a}^{r_b} \pi(r) \left\{ \Omega(\xi, r) + \alpha(r) - P_0 l^{-1} - \Omega(\xi^*) \right\} z(r) dr,
\]

subject to

\[
\Omega \left( \bar{\xi}, \bar{r} \mid r \right) = [1 - \kappa] \left\{ B_1 \left( \bar{\xi} \right) \left[ \bar{G} + \delta r [\mu_J - \mu_H] \right] + B_2 \left( \bar{\xi} \right) \mu_L + B_3 \left( \bar{\xi} \right) R \right\},
\]

\[
U \left( \bar{r} \mid r \right) = \pi \left( \bar{r} \right) \left\{ \left[ 1 - \bar{f} \right] \Omega \left( \bar{\xi}, \bar{r} \mid r \right) - P_0 \left( \bar{r} \mid r \right) l^{-1} \right\},
\]
\( U(r) \geq U(\tilde{r} \mid r) \quad \forall r, \tilde{r} \in [r_a, r_b], \)  

(35)

where \( P_0 \) is the value of the put option at \( t = 0 \), and with \( \tilde{f} \) being determined by:

\[
\hat{s}(\hat{\xi}) \left[ \tilde{f} \Omega(\hat{\xi}, r) + P_0(\tilde{r} \mid r) \right] = [1 + \omega + \triangle] R,
\]

(36)

and \( \Omega(\xi, r \mid r) \equiv \Omega(\xi, r), \quad U(r \mid r) \equiv U(r) \). Note that \( \Omega(\xi^*) \) is the total firm value of each firm that raises market financing using optimal disclosure \( \xi^* \). That is, the arbitrator maximizes the incremental surplus from mechanism design relative to the market-financing outcome.

To understand the arbitrator’s mechanism design problem, note that in (32) the arbitrator maximizes the expectation (taken with respect to \( r \) that the arbitrator does not know) of the total value of the firm \( \Omega \), plus its social value \( \alpha \), minus the deadweight cost of the put option \( P_0l^{-1} \), minus the value \( \Omega(\xi^*) \) attainable with market financing. (33) is simply the firm value when the firm’s true parameter is \( r \) and it reports \( \tilde{r} \) (which then implies a disclosure level of \( \tilde{\xi} \) associated with that \( \tilde{r} \)). In (34) we have the expected utility of the firm’s insiders. (35) is the global incentive compatibility (IC) constraint, and (36) is the competitive capital market pricing constraint.

Henceforth, for simplicity, we shall assume that \( L, H, \) and \( J \) are all uniform. Let us now write down the value of the put option (assuming that \( \zeta(r) > x_L \), something we will verify later as being associated with the optimal solution):

\[
P_0 = -\kappa \zeta(r) + [1 - \kappa] \left\{ B_1 \left[ \delta [1 - r] \int_{x_L}^{\zeta} [\zeta - x] dH - [1 - \delta] \int_0^{x_L} [\zeta - x] dL \right] \right\} \\
- [1 - \kappa] \left\{ B_2 \int_0^{x_L} [\zeta - x] dL + B_3 [\zeta - R] \right\}.
\]

(37)
Now,

$$\int_{x_L}^{\zeta} [\zeta - x] dH = \int_{x_L}^{\zeta} \frac{\zeta - x}{x_H - x_L} dx = \frac{(\zeta - x_L)^2}{2 [x_H - x_L]}.$$  

(38)

$$\int_0^{x_L} [\zeta - x] dL = \int_0^{x_L} \frac{\zeta - x}{x_L} dx = \zeta - \mu_L.$$  

(39)

Substituting (38) and (39) in (37) gives:

$$P_0 = -\kappa \zeta(r) + [1 - \kappa] \left\{ \frac{B_1 \delta [1 - r] [\zeta - x_L]^2}{2 [x_H - x_L]} - B_1 [1 - \delta] [\zeta - \mu_L] - B_2 [\zeta - \mu_L] - B_3 [\zeta - R] \right\}.$$  

(40)

We shall assume henceforth that the function $\phi(r) \equiv \frac{1 - Z(r)}{z(r)}$ satisfies:

$$\inf_r \left\{ \frac{1 - r}{\phi(\xi)} \right\} > \frac{1 - l}{l}.$$  

(41)

and

$$- \frac{\partial \phi(r)}{\partial r} < \frac{l}{1 - l}.$$  

(42)

These conditions simply assume that $l$ is large enough (the personal asset liquidation cost is not too high) and will be satisfied for many distributions (e.g. it holds for $l \in (0.5, 1)$ if $z$ is uniform).

We now present a result that allows us to express the global IC constraint (35) as a local constraint.
Lemma 4: The global IC constraint (35) is equivalent to:

1. \( U'(r) = \pi(r) \left[ (1 - \kappa) B_1 \delta [\mu_J - \mu_H] + \frac{\left[ l^{-1} - 1 \right][1 - \kappa] \delta B_1 [\zeta - x_L]^2}{2(x_H - x_L)} \right] \) for almost every \( r \in [r_a, r_b] \) and \( U'(r) > 0 \) wherever it exists.

2. \( U'' \geq 0 \) for almost every \( r \in [r_a, r_b] \)

3. (35) holds where \( U' \) does not exist.

The main contribution of this lemma is that it allows us to replace the infinite number of constraints embedded in the global IC constraint (35) with conditions involving the first and second derivatives of \( U \). This facilitates the subsequent analysis.

Lemma 5: The regulator’s mechanism design problem in (32)–(36) is equivalent to designing the functions \( \pi \) and \( \zeta \) to maximize:

\[
\begin{align*}
&\int_{r_a}^{r_b} \pi(r) \left\{ \phi(r) \left[ C_1 C_2 + C_1 \left[ l^{-1} - 1 \right] \left\{ \frac{[\zeta - x_L]^2}{2(x_H - x_L)} \right\} \right] \right\} z(r) \, dr \\
&+ \int_{r_a}^{r_b} \pi(r) \left\{ \frac{[1 + \omega + \Delta] R}{\bar{s}} + \alpha(r) - \Omega(\xi^*) - P_0(r) \right\} z(r) \, dr \\
&= \max_{\xi} \left\{ 1 - \tilde{f} \right\} \Omega(\xi | r) - P_0(r) l^{-1},
\end{align*}
\]

where \( C_1 \equiv [1 - \kappa] B_1 \delta \) and \( C_2 \equiv \mu_J - \mu_H \).

Given the allocation \( \{\pi(r), \zeta(r)\} \) in response to its reported \( r \), the firm chooses its disclosure \( \xi \) to maximize \( U(r) \), conditional on being allowed to participate, i.e. it solves

\[
\max_{\xi} \left\{ \Omega(\xi | r) - \frac{[1 + \omega + \Delta] R}{\bar{s}} - P_0(r) [l^{-1} - 1] \right\}.
\]
The arbitrator will take each firm’s (anticipated) post-reporting $\xi'(r)$ and solve for the 
\textit{ex ante} optimal mechanism accordingly. The following result characterizes the optimal 
mechanism.

**Proposition 6:** The optimal mechanism involves:

1. A put option strike price of

$$
\zeta(r) = x_L + \frac{[x_H - x_L] \left\{ \kappa + [1 - \kappa] \left[ B_1 [1 - \delta] + B_2 + B_3 \right] \right\}}{\left[ 1 - \kappa \right] B_1 \delta \left\{ [1 - r] - \phi(r) [l - 1 - 1] \right\}},
$$

which is greater than $x_L$ and increasing in $r$, and a digital option that makes investors 
long in the put and insiders short in the put when $x \in [x_L, x_H]$, and investors short in 
the put and insiders long in the put when $x < x_L$.

2. 

$$
\pi(r) = \begin{cases} 
1 & \text{if } r \geq r^* \in [r_a, r_b] \\
0 & \text{otherwise}
\end{cases}
$$

The intuition for this mechanism is as follows. Firms with lower values of $r$ want to 
masquerade themselves as firms with higher values of $r$. The optimal mechanism copes 
with this by making the put option strike price an increasing function of $r$. That is, for 
$x \in [x_L, x_H]$, the firm’s insiders (who are short in the put) have a higher liability under the 
put option they have sold to investors if they report a higher $r$. This mechanism is incentive 
compatible because it is less costly for the insiders of a firm with a higher true $r$ to be short 
in such an option than it is for the insiders of a firm with a lower true $r$.

In addition to this, the digital option makes insiders long in the put and investors short 
in the put when $x < x_L$. Although the put strike price is increasing in $r$, the value of this 
put is assessed equally by all firms regardless of $r$. That is, a higher put option strike price 
makes the option more valuable, but how much higher the option is valued does not depend 
on the firm’s $r$. So it reduces the expected cost of personal asset liquidation equally for all
insiders, thereby increasing the expected utility of insiders. The probability of being allowed to participate in this mechanism is 1 as long as the mechanism enables the arbitrator to achieve a higher value of the objective function than with direct market financing. Otherwise, the firm is asked to go for the direct market financing option.

This mechanism helps to overcome two major impediments to financing risky R&D—convincing investors that there is enough upside in the success of the R&D to make it attractive for them to invest, and convincing the entrepreneur (e.g. the manager of a biotech firm) that there is sufficient downside protection against the failure of the R&D that it is worthwhile to undertake it.

5.3 Interpretation and Intuition

The core intuition behind why this mechanism works can be thought of as follows. Roughly speaking, there are three ranges of R&D outcomes in the model: very low cash flows, intermediate cash flows, and very high cash flows. The probability of achieving the very high cash flows is private information for the firm’s insiders, and varies in the cross-section of firms. Firms with low probabilities have an obvious incentive to misrepresent themselves as having high probabilities of achieving very high cash flows. By asking firms that report higher probabilities of achieving very high cash flows to provide investors greater insurance against intermediate cash flows, the optimal mechanism design deters such misrepresentation. Of course, since R&D outcomes are uncertain, providing such insurance to investors

\[25\] In this analysis we have taken the reservation utilities of the firms for participating in the mechanism as exogenous. This is in contrast to the Phillipon and Skreta (2012) and Tirole (2012) models in which reservation utilities are endogenous in the sense that they depend on the mechanism itself. In these models, the mechanism is meant to deal with the market freeze caused by the lowest quality firms, and in Tirole (2012), for example, the government buys up the weakest assets. While we also allow the market to be open and hence market financing is an alternative to the mechanism for each firm, in our model the mechanism is designed in such a way that it is optimally preferred to market financing by the highest quality firms, and it is only the firms at the lowest end of the quality spectrum (with respect to the R&D payoff enhancement) that go to the market because the mechanism cannot do incrementally better than market financing for these firms. Moreover, the mechanism ensures that any firm that uses the mechanism gets an expected utility that is higher than that with market financing. So, no matter what the design of the mechanism, the firms that are not part of it cannot raise market financing for the R&D project enhancement, and thus reservation utilities for participating in the mechanism are unaffected by the market option.
is costly for the firm’s insiders. To offset this cost, investors in turn insure the firm’s insiders against very low cash flows. Thus, potential underinvestment in R&D is discouraged from both the standpoint of insiders underinvesting due to high possibility of failure, and investors underinvesting due to suspicion of too low a probability of very high payoffs (adverse selection).

More formally, our mechanism can functionally be interpreted as an exchange of put options (insurance contracts) between investors and insiders. One contract is offered by insiders to investors, and insures investors against the possibility that the firm misrepresents its chances of the R&D-enhancement succeeding. Since the strike price is increasing in $r$, this cost makes it progressively more onerous for a firm to misrepresent itself as a high-$r$ firm, thus inducing it to truthfully report its value of $r$. Put another way, the payoff range of this insurance contract only occurs when $x$ achieves a high cash flow distribution (with cdf $H$). Firms with a high likelihood of R&D-enhancement success will not expect to fall into this region (since they will have cash flow $x$ distributed according to cdf $J$). However, firms with a low likelihood of R&D-enhancement success have a high chance of falling into this region. Of these firms, the ones that truthfully report their (low) value of $r$ will not be invited to participate in the mechanism.$^{26}$ The ones that choose to participate by misrepresenting their value of $r$ as being higher will be required to provide an insurance contract to investors. This insurance contract therefore helps to incentivize investors to provide financing for the R&D-enhancing investment, by protecting them against the risk of financing unsound firms, or firms that may be sound but have a relatively low likelihood of achieving the very high payoff associated with R&D-enhancement success.

The other contract is offered by investors to insiders, and insures insiders against a poor cash-flow outcome in the final stage of R&D. For insiders, this contract offers a more flat net payoff that offsets disappointing (commercialized) R&D results in the final stage. Investors

$^{26}$It should be noted that the design of the mechanism does not change the behavior of the firms that do not participate in the mechanism and only go to the market to raise financing. In other words, for the firms not investing in the R&D payoff enhancement (and thus not participating in the mechanism), the investment and capital structure analysis of Section 4 of the paper still holds.
are willing to provide this “downside” insurance in order to induce insiders to undertake the R&D-enhancement, which makes their initial investment pay off even more. Investors’ willingness to provide this insurance therefore also increases in the probability $r$ because this makes the upside more likely, and thus investors are willing to pay more to enable it.

The interpretation of our mechanism in terms of insurance contracts and guarantees corresponds in part to the recent use of similar financial contracts in the biopharma sector, but also offers insights into how these contracts could be augmented. For example, a financing innovation for investors is called an “FDA swap”, which provides firms insurance against the failure of a drug to get FDA approval (see Philipson (2015) for details). Another innovation is “Phase 2 development insurance”, which is offered to small biotech firms in exchange for an equity stake in the firm, and pays out in the event that a drug candidate fails Phase 2 R&D trials. These contracts resemble the put sold by investors to insiders. Our mechanism shows the value of such contracts, but also indicates that an appropriate exchange of insurance contracts between firms and investors can potentially overcome impediments to financing related to adverse selection, and lead to an improvement in R&D outcomes. That is, by adding the put sold by insiders to investors, adverse selection problems can be solved—insiders will no longer have an incentive to overstate the upside potential of their R&D.

Overall, our mechanism highlights the value of credible precommitment to a coordinating mechanism between firm insiders and investors, which can increase R&D investments. In practice, the arbitrator in our mechanism could be any entity which plays an intermediation role, bringing firms and investors together, extracting the true prospects of some R&D investments in a way that the market cannot, and enforcing the ex ante commitments made to the mechanism. This role could practically be played, for example, by the government, or a third-party entity like an exchange or consortium of firms.\textsuperscript{27} To the extent that existing contracts do not reflect the kind of bilateral exchange of insurance that our analysis says is

\textsuperscript{27}For example, financial exchanges such as the Chicago Mercantile Exchange, which serve as an intermediary to bring two counterparties together in a financial transaction, can be seen as playing a similar role.
optimal, the implication is that the empirically-documented underinvestment in R&D (e.g. Brown and Lerner (2010)) may be attenuated by augmenting the contract space along the lines indicated here.

6 Conclusion

In this paper, we develop a model of optimal investment and capital structure for R&D-intensive firms. We examine a setting with asymmetric information, moral hazard, and adverse selection, where firms need to raise large amounts of capital to invest in an R&D project with long-term staged investments and low probabilities of success—features that typify many R&D-intensive firms in industries such as biopharma. Adverse selection in this setting is partially endogenized, as firms can reduce it by disclosing information about their projects; however, this also generates a cost to firms, as private information is revealed to competitors.

We use this model to explain various stylized facts about firms in this environment. First, these firms have lower leverage ratios than other firms, and they rely largely on internal funds and equity. Second, they have large amounts of cash. Third, there is a “funding gap” or underinvestment in R&D. In explaining these stylized facts, we establish the optimal pecking order of securities with market financing: equity dominates debt, and firms also seek to hold excess cash for future investments rather than tap the external finance market. However, there are still socially valuable project enhancements that firms do not undertake in equilibrium with market financing.

We then ask whether there is a non-market solution to the underinvestment problem. For this analysis, we take a mechanism design approach, and show that an arbitrator may design a mechanism which resolves this friction and induces firms to undertake the additional investment in R&D. Specifically, a mechanism consisting of insiders buying and selling put options, in combination with equity, allows the firm to commit to making the socially ben-
eficial R&D enhancement. The introduction of this mechanism improves welfare relative to market financing because it eliminates underinvestment. The analysis also more generally highlights the potential benefit of a coordinating mechanism between investors and firms, which can induce a precommitment in R&D financing.

The mechanism developed in this paper provides a broader theoretical justification for recent alternative methods of financing R&D, which may allow additional socially valuable research to be funded. This is in line with Fernandez, Stein, and Lo (2012) and Fagnan et al. (2013), who also explore financing vehicles that are alternatives to traditional market financing for funding drug development in the biopharma sector. Future research could examine ways to synthesize and incorporate the ideas of these models into practice.
Appendix

Proof of Proposition 1: Suppose this were not true. Then suppose the firm receives the signal at \( t = 2 \) that its first-stage R&D produced good results. If it now raises the investment \( R \) that it needs by accessing external financing, it will become publicly known that the first-stage R&D was successful. Competitive entry at \( t = 2 \) means that the firm’s expected project value will drop to

\[
\int_{0}^{x_{L}} x dL = R + \varepsilon, \tag{A.1}
\]

and thus the NPV of the investment is \( \varepsilon \). Since \( \varepsilon \) is arbitrarily small, we have that \( \varepsilon < \omega R \), so the firm will not make the initial investment at \( t = 0 \) in the first place. This means that if the firm does invest in R&D at all, it will raise the entire financing needed for the two stages, \([1 + \omega] R\), at \( t = 0 \), so as to avoid revealing the outcome of the first-stage R&D publicly at \( t = 2 \). ■

Proof of Lemma 1: Let us now solve for \( \hat{s}(\xi) \). Note that:

\[
\hat{s}(\xi) = \Pr(\text{firm sound} \mid \phi = \text{sound}) \\
= \frac{\Pr(\phi = \text{sound} \mid \text{firm sound}) \Pr(\text{firm sound})}{\Pr(\phi = \text{sound})} \\
= \frac{p(\xi) s}{p(\xi) s + [1 - p(\xi)] [1 - s]}, \tag{A.2}
\]

\[
\frac{\partial \hat{s}}{\partial \xi} = \frac{p' s [1 - s]}{[p(\xi) s + [1 - p(\xi)] [1 - s]]^2} > 0. \tag{A.3}
\]

Note further that:

\[
\frac{\partial^2 \hat{s}}{\partial \xi^2} = \frac{D \{p'' s[1 - s] - 2p' s[1 - s] [p' s - p'[1 - s]]\}}{D^2}, \tag{A.4}
\]

where

\[
D \equiv [p(\xi) s + [1 - p(\xi)] [1 - s]]^2. \tag{A.5}
\]

Note that \( \partial^2 \hat{s}/\partial \xi^2 < 0 \) since \( p'' < 0 \), \( p' > 0 \), and \( s > 0.5 \). ■

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Proof of Proposition 2: Combining (11) and (12), we can write the objective function as:

$$\Omega (\xi) - [1 + \omega] R [\hat{s} (\xi)]^{-1}.$$  \hspace{1cm} (A.6)

The first-order condition is:

$$\left[ \frac{\partial \Omega}{\partial \xi} \right] + [1 + \omega] R [\hat{s} (\xi)]^{-2} \left[ \frac{\partial \hat{s}}{\partial \xi} \right] = 0.$$  \hspace{1cm} (A.7)

The second-order condition is:

$$\left[ \frac{\partial^2 \Omega}{\partial \xi^2} \right] - 2 [1 + \omega] R [\hat{s} (\xi)]^{-3} \left[ \frac{\partial \hat{s}}{\partial \xi} \right]^2 + [1 + \omega] R [\hat{s} (\xi)]^{-2} \left[ \frac{\partial^2 \hat{s}}{\partial \xi^2} \right] < 0.$$  \hspace{1cm} (A.8)

Now,

$$\frac{\partial \Omega}{\partial \xi} = - [1 - \kappa] \theta^\prime (\xi) \left\{ \bar{q} \bar{G} + [1 - \bar{q}] R - q \int x dL - [1 - \bar{q}] R \right\}$$

$$= - [1 - \kappa] \theta^\prime (\xi) \left\{ \bar{q} \bar{G} - q \int x dL + qR - \bar{q}R \right\}$$

$$= - [1 - \kappa] \theta^\prime (\xi) \left\{ \bar{q} \left[ \bar{G} - R \right] - q \int x dL + qR \right\}$$

$$< 0,$$  \hspace{1cm} (A.9)

since \(\theta^\prime > 0, \ \bar{G} > R, \) and \(R > \int x dL.\) Moreover, defining \(A_1 \equiv \bar{q} \left[ \bar{G} - R \right] - q \int x dL + qR,\) we have:

$$\frac{\partial^2 \Omega}{\partial \xi^2} = - [1 - \kappa] \theta^\prime (\xi) A_1 < 0,$$  \hspace{1cm} (A.10)

since \(\theta^\prime > 0.\) Since \(\partial \hat{s}/\partial \xi < 0,\) it is clear now that (A.8) holds. The fact that \(\xi^*\) is in the interior follows from the Inada-type conditions.  \(\blacksquare\)

Proof of Proposition 3: Given the out-of-equilibrium belief stipulated in the proposition, it is clear that the pooling equilibrium is sequential, since each firm’s equilibrium expected utility is higher than if it deviates from the equilibrium strategy.  \(\blacksquare\)
Proof of Proposition 4: The first-order condition corresponding to (20) is:

\[
\frac{\partial \Omega_D(\xi)}{\partial \xi} + [1 + \omega] R [\dot{s}(\xi)]^{-2} \left[ \frac{\partial \dot{s}}{\partial \xi} \right] = 0.
\]  
(A.11)

The second-order condition is:

\[
\frac{\partial^2 \Omega_D(\xi)}{\partial \xi^2} - 2[1 + \omega] R [\dot{s}(\xi)]^{-3} \left[ \frac{\partial \dot{s}}{\partial \xi} \right]^2 + [1 + \omega] R [\dot{s}(\xi)]^{-2} \left[ \frac{\partial^2 \dot{s}}{\partial \xi^2} \right] < 0.
\]  
(A.12)

It can be verified that, since \( A_2 > A_3 \), \( \frac{\partial^2 \Omega_D(\xi)}{\partial \xi^2} < 0 \), and the second-order condition in (A.12) is satisfied. ■

Proof of Proposition 5: Take the optimal solution, \( \xi^o \), with debt financing and evaluate the firm’s objective function in (20) at the optimum:

\[
\Omega_D(\xi^o) - [1 + \omega] R [\dot{s}(\xi^o)]^{-1}.
\]  
(A.13)

Now evaluate (11) at \( \xi = \xi^o \):

\[
\Omega(\xi^o) - [1 + \omega] R [\dot{s}(\xi^o)]^{-1}.
\]  
(A.14)

Thus, equity will strictly dominate debt if:

\[
\Omega(\xi^o) > \Omega_D(\xi^o),
\]  
(A.15)

given that

\[
\Omega(\xi^*) \geq \Omega(\xi^o).
\]  
(A.16)

Now, after simplification and using (20), we see that (A.15) will hold if:

\[
[1 - \kappa] \left\{ \bar{q} \left[ 1 - \theta(\xi^o) \right] \left[ \frac{1 - \delta}{2} \right] [G - R] + q \theta(\xi) \left[ \frac{1 - \delta}{2} \right] [\mu_L - R] \right\} > \kappa \left\{ \Pr (y = 0 \mid 0) R + \Pr (y = 0 \mid \delta) R \right\}
\]  
(A.17)

\[
= \kappa R
\]  
(A.17)
For a fixed $\mu_H$, it is clear that (A.17) will hold for $\kappa$ low enough, since it holds for $\kappa = 0$, so it holds by continuity for $\kappa$ low enough. Similarly, for a fixed $\kappa$, note that the left-hand side of (A.17) is strictly increasing in $\mu_H$. Thus, for $\mu_H$ high enough, (A.17) will hold. Finally, it is also clear from (A.17) that the left-hand side of (A.17) is decreasing in $\delta$.

Finally, for $\mu_H$ large enough and $\kappa$ small enough, it can be verified that $|\partial \Omega_D(\xi)/\partial \xi| < |\partial \Omega(\xi)/\partial \xi|$, with $\partial \Omega_D(\xi)/\partial \xi < 0$ and $\partial \Omega(\xi)/\partial \xi < 0$. Thus, $\partial \hat{s}/\partial \xi$ in (A.7) must exceed the $\partial \hat{s}/\partial \xi$ in (A.11). Since $\partial^2 \hat{s}/\partial \xi^2 < 0$, it follows that $\xi_o > \xi^*$. ■

**Proof of Lemma 2:** Note first that

\[
\frac{\partial \Omega}{\partial \xi} = -[1 - \kappa] \theta' \left\{ \left[ \bar{G} + \delta r [\mu_J - \mu_H] \right] \bar{q} - q \mu_L + R \left[ 1 - \bar{q} - 1 + \bar{q} \right] \right\}
\]

\[
= -[1 - \kappa] \theta' \left\{ \bar{q} \delta r [\mu_J - \mu_H] + [\bar{q} - q] \left[ \bar{G} - R \right] + q \left[ G - \mu_L \right] \right\}
\]

\[
< 0,
\]

(A.18)

and

\[
\frac{\partial^2 \Omega}{\partial \xi^2} = -[1 - \kappa] \theta'' \left\{ \bar{q} \delta r [\mu_J - \mu_H] + [\bar{q} - q] \left[ \bar{G} - R \right] + q \left[ G - \mu_L \right] \right\}
\]

\[
< 0,
\]

(A.19)

since $\theta'' > 0$. Now substituting (28) in (26), we can write the firm’s objective function as:

\[
\Omega(r, \xi) - [1 + \omega + \triangle] R [\hat{s}(\xi)]^{-1}.
\]

(A.20)

The first-order condition for the optimal $\xi$, call it $\xi^*$, is:

\[
\frac{\partial \Omega}{\partial \xi} + [1 + \omega + \triangle] R [\hat{s}(\xi)]^{-2} \left[ \frac{\partial \hat{s}}{\partial \xi} \right] = 0.
\]

(A.21)

The second-order condition is:

\[
\Theta \equiv \frac{\partial^2 \Omega}{\partial \xi^2} - 2 [1 + \omega + \triangle] R [\hat{s}(\xi)]^{-3} \left[ \frac{\partial \hat{s}}{\partial \xi} \right]^2 + [1 + \omega + \triangle] R [\hat{s}(\xi)]^{-2} \left[ \frac{\partial^2 \hat{s}}{\partial \xi^2} \right] < 0.
\]

(A.22)
Since \( \partial^2 \Omega / \partial \xi^2 < 0 \) and \( \partial^2 \hat{s} / \partial \xi^2 < 0 \), it is clear that (A.22) holds. Thus, a unique optimum \( \xi^* \) exists.

Now, totally differentiate the first-order condition (A.21) to write

\[
\Theta \left[ \frac{d\xi^*}{dr} \right] + \frac{\partial^2 \Omega}{\partial \xi \partial r} = 0, \tag{A.23}
\]

which gives

\[
\frac{d\xi^*}{dr} = - \left[ \frac{\partial^2 \Omega}{\partial \xi \partial r} \right] / \Theta. \tag{A.24}
\]

Using (A.18), we can write:

\[
\frac{\partial^2 \Omega}{\partial \xi \partial r} = - \left[ 1 - \kappa \right] \theta' \left\{ \left[ \bar{q} - q \right] \delta \left[ \mu_J - \mu_H \right] \right\} < 0. \tag{A.25}
\]

Since \( \Theta < 0 \), it follows from (A.24) and (A.25) that \( d\xi^*/dr < 0 \). ■

**Proof of Lemma 3:** Consider \( r_1 < r_2 \) and suppose the arbitrator asks each firm to report its \( r \) and then implement the first-best solution. Let \( \xi_i \) and \( f_i \) be the disclosure level and ownership fraction sold by the firm corresponding to a report of \( r_i \). Then if the \( r_1 \) firm reports \( r_2 \), its insiders’ expected utility is

\[
[1 - f_2] \Omega (r_1, \xi_2) > [1 - f_2] \Omega (r_1, \xi_1) > [1 - f_1] \Omega (r_1, \xi_1), \tag{A.26}
\]

where the first inequality follows since \( \Omega \) is decreasing in \( \xi \) and \( \xi_1 > \xi_2 \) (which follows from Lemma 2, which states that the first-best \( \xi \) is strictly decreasing in \( r \)), and the second inequality follows since \( f_1 > f_2 \). Note that \( f_1 > f_2 \) follows from (28) and the fact that \( \Omega(r, \xi) \) defined in (27) is strictly increasing in \( r \). Thus, the \( r_1 \) firm will misreport its type as \( r_2 \). ■
Proof of Lemma 4: Substituting from (36) into (34), we can write (suppressing $\xi$ as an argument of the functions):

$$
U(r) = \left[ \Omega(r) - \frac{[1 + \omega + \triangle]}{\hat{s}} + P_0 - P_0 l^{-1} \right] \pi(r)
$$

$$
= \pi(r) \left[ \Omega(r) - \frac{[1 + \omega + \triangle]}{\hat{s}} R - \lfloor l^{-1} - 1 \rfloor P_0 \right]. \tag{A.27}
$$

We will first show that (35) implies parts 1 and 2 of the lemma. From (35) we have that $U(r | r) \geq U(\bar{r} | r)$, so:

$$
\begin{align*}
\pi(r) & \left[ \Omega(r) - \frac{[1 + \omega + \triangle]}{\hat{s}} R - \lfloor l^{-1} - 1 \rfloor P_0(r) \right] \\
& \geq \pi(\bar{r}) \left[ \Omega(\bar{r} | r) - \frac{[1 + \omega + \triangle]}{\hat{s}} R - \lfloor l^{-1} - 1 \rfloor P_0(\bar{r}) \right] + [1 - \kappa]B_1 \left( \bar{\xi} \right) \delta r [\mu_J - \mu_H] \pi(\bar{r}) \\
& \quad - \lfloor l^{-1} - 1 \rfloor [1 - \kappa]B_1 \left( \bar{\xi} \right) \left[ \frac{\delta[1 - r][\zeta - x_L]^2}{2[x_H - x_L]} \right] \pi(\bar{r}) \\
& = U(\bar{r}) + [1 - \kappa]B_1 \delta \left[ r - \bar{r} \right] \pi(\bar{r}) \left[ \mu_J - \mu_H \right] + \lfloor l^{-1} - 1 \rfloor \left\{ \frac{[\zeta - x_L]^2}{2[x_H - x_L]} \right\}. \tag{A.28}
\end{align*}
$$

Thus,

$$
U(r) - U(\bar{r}) \geq [r - \bar{r}] N(\bar{r}), \tag{A.29}
$$

where

$$
N(\bar{r}) \equiv \pi(\bar{r}) [1 - \kappa]B_1 \delta \left[ \mu_J - \mu_H \right] + \lfloor l^{-1} - 1 \rfloor \left\{ \frac{[\zeta - x_L]^2}{2[x_H - x_L]} \right\}. \tag{A.30}
$$

Similarly (reversing the roles of $r$ and $\bar{r}$):

$$
U(\bar{r}) - U(r) \geq [\bar{r} - r] N(r), \tag{A.31}
$$

which implies

$$
U(r) - U(\bar{r}) \leq [r - \bar{r}] N(r). \tag{A.32}
$$
Combining (A.29) and (A.32) yields:

\[
[r - \tilde{r}] N (\tilde{r}) \leq U(r) - U(\tilde{r}) \leq [r - \tilde{r}] N(r).
\]  

(A.33)

Inspection of (A.33) shows that if \( r > \tilde{r} \), then the function \( N(r) \) is non-decreasing. Given this monotonicity, we can divide through by \( r - \tilde{r} \) and take the limit as \( \tilde{r} \to r \) to write:

\[
\lim_{\tilde{r} \to r} \frac{U(r) - U(\tilde{r})}{\tilde{r} - r} = U'(r) = N(r) > 0 \text{ almost everywhere.}
\]  

(A.34)

Since \( N(r) \) is non-decreasing, it follows that \( U'' \geq 0 \) almost everywhere. Thus we have shown that (35) implies parts 1 and 2 of the Lemma.

Next, we will show that parts 1 and 2 of the lemma imply (35). Note that

\[
U(r \mid r) - U(\tilde{r} \mid r) = U(r \mid r) - U(\tilde{r} \mid r) + [r - \tilde{r}] N(\tilde{r})
\]

\[
= \int_{\tilde{r}}^{r} U'(t \mid t) dt - [r - \tilde{r}] U'(r \mid \tilde{r})
\]

\[
\geq 0,
\]  

(A.35)

using part 1 of the lemma, \( U'' \geq 0 \), and the mean value theorem for integrals. □

**Proof of Lemma 5:** Since the global I.C. constraint has been shown to be equivalent to \( U'(r) = N(r) \) almost everywhere in the previous lemma, let us integrate that condition to obtain:

\[
\int_{r_a}^{r} U'(\tilde{r} \mid \tilde{r}) d\tilde{r} = \int_{r_a}^{r} N(\tilde{r}) d\tilde{r},
\]  

(A.36)

which means

\[
U(r) - U(r_a) = \int_{r_a}^{r} N(\tilde{r}) d\tilde{r}
\]

\[\implies U(r) = U(r_a) + \int_{r_a}^{r} N(\tilde{r}) d\tilde{r}.
\]  

(A.37)
Taking the expectation of (A.37) yields:

\[
\int_{r_a}^{r_b} U(r) z(r) \, dr = U(r_a) + \int_{r_a}^{r_b} \left[ \int_{r_a}^{r} N(t) \, dt \right] z(r) \, dr
\]
\[
= U(r_a) + \int_{r_a}^{r_b} N(t) \left[ \int_{t}^{r_b} z(r) \, dr \right] \, dt
\]
\[
= U(r_a) + \int_{r_a}^{r_b} \phi(r) N(r) z(r) \, dr,
\]
(A.38)

where \( \phi(r) \equiv \frac{1 - Z(r)}{z(r)} \). Now we know from (34) that

\[
\pi(r) \left[ \Omega(\xi, r) - P_0(r) l^{-1} \right] = U(r) + \pi(r) f \Omega(r).
\]
(A.39)

Substituting in (A.39) for \( f \Omega \) from (36) gives us:

\[
\pi(r) \left[ \Omega(\xi, r) - P_0(r) l^{-1} \right] = U(r) + \pi(r) \left[ \frac{1 + \omega + \Delta}{s} R \hat{s} + \alpha(r) - \Omega(\xi^*) - P_0(r) \right] z(r) \, dr.
\]
(A.40)

Substituting (A.40) into (32) yields the objective function:

\[
\int_{r_a}^{r_b} \left\{ U(r) + \pi(r) \left[ \frac{1 + \omega + \Delta}{s} R \hat{s} + \alpha(r) - \Omega(\xi^*) - P_0(r) \right] \right\} z(r) \, dr.
\]
(A.41)

The arbitrator can give insiders of the lowest type \((r = r_a)\) their expected utility with market financing. Let this expected utility be \( \pi_a \). Then set \( U(r_a) = \pi_a \) and substitute (A.38) in (A.41) above to get

\[
\pi_a + \int_{r_a}^{r_b} \phi(r) N(r) \left[ \frac{1 + \omega + \Delta}{s} R \hat{s} + \alpha(r) - \Omega(\xi^*) - P_0(r) \right] z(r) \, dr.
\]
(A.42)

Now use (A.30) and write

\[
N(r) = \pi(r) C_1 \left[ C_2 + \left[ l^{-1} - 1 \right] \left\{ \frac{(\zeta - x_L)^2}{2 [x_H - x_L]} \right\} \right],
\]
(A.43)
so that the arbitrator’s objective function (A.42) can be written as:

$$\pi_a + \int_{r_a}^{r_b} \pi(r) \left\{ \phi(r) \left[ \frac{[\zeta - x_L]^2}{2[x_H - x_L]} \right] \right\} + \frac{[1 + \omega + \triangle] R}{\dot{s}} + \alpha(r) - \Omega(\xi^*) - P_0(r) \right\} z(r) \, dr. \quad (A.44)$$

This completes the proof since maximizing (A.44) is equivalent to maximizing (43) because \( \pi_a \) is a constant (i.e. independent of the mechanism design functions).

Proof of Proposition 6: Let us first prove (46). From optimal control theory, we know that the value function \( \zeta \) that maximizes (A.44) is the one that involves maximizing the integral pointwise. Thus, the first-order condition for \( \zeta \) is:

$$\phi(r) \left[ l^{-1} - 1 \right] \left[ 1 - \kappa \right] B_1 \delta \left[ \zeta - x_L \right] [x_H - x_L]^{-1} + \kappa - [1 - \kappa] \left\{ B_1 \delta [1 - r] \left[ \zeta - x_L \right] [x_H - x_L]^{-1} - B_1 \left[ 1 - \delta \right] - B_2 - B_3 \right\} = 0, \quad (A.45)$$

which yields (46) upon rearranging. The second-order condition is:

$$\phi(r) \left[ l^{-1} - 1 \right] \left[ 1 - \kappa \right] B_1 \delta \left[ x_H - x_L \right]^{-1} - [1 - \kappa] B_1 \delta [1 - r] \left[ x_H - x_L \right]^{-1} < 0, \quad (A.46)$$

which requires

$$[1 - \kappa] B_1 \delta \left[ x_H - x_L \right]^{-1} \left\{ \phi(r) \left[ l^{-1} - 1 \right] - [1 - r] \right\} < 0, \quad (A.47)$$

which holds since (42) tells us that

$$\frac{1 - r}{\phi(r)} > l^{-1} - 1. \quad (A.48)$$

Moreover, \( \partial \zeta / \partial r > 0 \), also given (42). Inspection of (A.44) also reveals that the arbitrator will set \( \pi = 1 \) whenever the term multiplying \( \pi(r) \) in (A.44) is positive and set \( \pi = 0 \) otherwise. Since \( U'(r) > 0 \) in equilibrium, it follows that \( \exists \ r^* \) such that \( \pi(r) = 1 \ \forall \ r \geq r^* \) and \( \pi(r) = 0 \) otherwise.

\[ \blacksquare \]
References


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