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ABSTRACT

We develop a theory of optimal financing for R&D-intensive firms that uses their unique features—large capital outlays, long gestation periods, high upside, and low probabilities of R&D success—that explains three prominent stylized facts about these firms: their relatively low use of debt, large cash balances, and underinvestment in R&D. The model relies on the interaction of the unique features of R&D-intensive firms with three key frictions: adverse selection about R&D viability, asymmetric information about the upside potential of R&D, and moral hazard from risk shifting. We establish the optimal pecking order of securities with direct market financing. Using a tradeoff between tax benefits and the costs of risk shifting for debt, we establish conditions under which the firm uses an all-equity capital structure and firms raise enough financing to carry excess cash. A firm may use a limited amount of debt if it has pledgeable assets in place. However, market financing still leaves potentially valuable R&D investments unfunded. We then use a mechanism design approach to explore the potential of intermediated financing, with a binding precommitment by firm insiders to make costly ex post payouts. A mechanism consisting of put options can be used in combination with equity to eliminate underinvestment in R&D relative to the direct market financing outcome. This optimal intermediary-assisted 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.

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1 Introduction

What is the optimal way to finance an R&D-intensive firm? This question is especially urgent given the economic and social value created by technological innovation, and the evidence of a “funding gap” for innovation that creates underinvestment in R&D (see Hall and Lerner (2010)). Because this funding gap is only partly mitigated by venture capital, many potentially transformative technologies are not being realized or even pursued.¹ Is there a market failure of existing financing mechanisms that systematically creates a “Valley of Death” for early stage R&D funding, and if so, how can the financing mix address this failure? We provide an answer in this paper.

It has been suggested that this funding gap arises from the following features of R&D-intensive firms:

1. R&D is expensive. For example, the development cost of a single new drug in the biopharmaceutical sector is estimated to be \$2.6 billion (see DiMasi, Grabowski, and Hansen (2014)).²
2. R&D often has long gestation periods, consisting of multiple phases of binary outcomes. Moreover, R&D investments involve a sequence of escalating resource commitments, requiring substantial specialized knowledge (see DiMasi et al. (1991) and Kerr and Nanda (2015)). In contrast, other industries, such as manufacturing, have a more continuous investment process—continuous both in time and in funding.

¹Brown, 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. (2017) document that pharmaceutical and biotechnology companies have a significant exposure to the well-being of the economy. Kerr and Nanda (2015) provide a review of the literature related to financing and innovation. 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.

²DiMasi and Grabowski (2007) estimated the average capitalized cost of a new drug to exceed \$1 billion as of the mid-2000s, 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.

3. R&D investments generally have low probabilities of success (see DiMasi et al. (1991, 2013)), but high payoffs conditional on success (e.g. Grabowski, Vernon, and DiMasi (2002), DiMasi, Grabowski, and Vernon (2004), and Kerr and Nanda (2015)).
4. Large R&D outlays rely on external financing.³

This last feature exposes R&D-intensive firms to many financing frictions, including adverse selection related to the payoff potential of R&D and moral hazard from risk shifting. These financing frictions have important capital structure implications.

The goal of this paper is threefold: to theoretically examine how these financing frictions interact with the unique features of R&D-intensive firms to influence their capital structure, how residual adverse selection problems may be left unresolved by standard debt and equity contracts used in the optimal capital structure, and how intermediary-assisted non-market solutions may be used to reduce the funding gap created by these unresolved adverse selection problems. We show that the optimal financing for R&D-intensive firms will involve a *combination* of market financing and a novel form of financial intermediation.

Our model has three key features. The first is taxes. R&D investments must be expensed, and these expenses are tax-deductible, as are payments to bondholders. Second, there is adverse selection about R&D quality, with the firm's insiders knowing more than outside investors. Third, the firm can engage in unobservable risk shifting to expropriate wealth from bondholders, which is inefficient and reduces total firm value.

A firm makes the following decisions: how much financing to raise at the outset, and how much of the financing to raise from debt and how much from equity. We show that the firm will raise all of its current and future financing needs upfront, investing some of it initially, and carrying the rest as cash. We also identify the conditions under which the pecking order of financing is first internal cash, then equity, and then debt. As a result, all initial financing is raised through (outside) equity.

³See Lerner, Shane, and Tsai (2003), Brown, Fazzari, and Petersen (2009), and Acharya and Xu (2013) for empirical evidence of the reliance of these firms on the broader equity market. Also see Thakor et al. (2017) for empirical evidence of this for pharmaceutical and biotechnology companies.

The optimal capital structure balances the cost of risk shifting with debt against the value of the debt tax shield. However, even with this familiar tradeoff, we show a reversal of the Myers and Majluf (1984) debt-equity pecking order for R&D-intensive firms. Two factors contribute to this reversal. First, R&D expenses are tax-deductible, and we show that this reduces the value of the debt tax shield. Second, risk shifting is considerably easier for firms with significant R&D than for other kinds of projects, as we show later. It is also more difficult to detect, due to the technical nature of R&D and the relatively low probabilities of success of R&D projects. Absent pledgeable assets in place, our analysis generates an optimal capital structure that is all-equity under conditions that correspond closely to those encountered with R&D-intensive firms. Specifically, in these circumstances the cost of debt due to risk shifting is strictly greater than the (concave-in-debt) value of the debt tax shield for all values of debt. Pledgeable assets in place introduce some debt into the capital structure, with the amount of debt being limited to the amount of pledgeable assets. We also show that some asymmetric information remains unresolved with market financing, resulting in underinvestment in R&D.

An R&D-intensive firm raises more financing than it needs for immediate investment—and thus carries extra cash—because the more the firm knows relative to the market, the more its financing decision will reveal to its competitors (e.g. Kamien and Schwartz (1978)). The idea is that, despite substantial adverse selection costs from raising external financing at an early date, 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—since the act of raising financing later conveys information about R&D success. This justification is distinct from either precautionary or tax-related motives for holding cash.⁴

⁴For 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 inadvertent signaling of R&D success in inducing firms to hold excess cash—thus, a firm in our setup will want to hold cash to avoid this cost 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 related to other frictions such as the tax expensing of R&D and risk shifting.

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 (2016)), 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—the funding gap—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. Begenau and Palazzo (2016) and Thakor and Lo (2016)).⁵ Fourth, R&D-intensive firms do use external financing, relying on stock issues to finance R&D (e.g. Brown, Fazzari, and Petersen (2009)), and hence do not display the often-discussed aversion of other firms to equity issuance (e.g. Myers and Majluf (1984)).

Our capital structure result differs from the standard theoretical argument that R&D-intensive firms avoid debt because knowledge assets have little collateral value (e.g. Hart and Moore (1994) and Rampini and Viswanathan (2010)). The importance of tangible assets for debt capacity is well documented empirically. However, Lim, Macias, and Moeller (2014) find that both tangible and intangible assets are positively related to leverage, with intangible assets supporting half as much debt as tangible assets. Consistent with this fact, R&D-intensive firms are able to rely on their stock of knowledge patents as a source of collateral (see Mann (2014)). Moreover, Byoun, Moore, and Xu (2012) find that debt-free firms do have tangible assets to offer as collateral and have enough profitability to pay high dividends.⁶ All of these findings point to factors other than asset tangibility that may influence a firm’s debt decision.

The empirically-documented “R&D funding gap” under market financing that arises in our analysis leads us directly to the next phase of our analysis. We explore whether it is

⁵Also see Brown and Petersen (2011) and Bates, Kahle, and Stulz (2009) for evidence that greater R&D intensity leads to higher cash balances. 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 an important driver of this, which is consistent with the evidence of Thakor and Lo (2016).

⁶In addition, even amongst R&D-intensive firms with qualitatively similar levels of asset tangibility, there is a large cross-sectional dispersion of leverage ratios (e.g. Thakor and Lo (2016) and Thakor et al. (2017)).

possible to improve upon traditional capital market funding by introducing an intermediary that is able to extract a *binding precommitment* from the firm’s insiders to make costly ex post payouts from their personal wealth endowment. We also design a mechanism to elicit truthful reports from firms about their private information on the expected cash flow enhancement from an additional R&D investment.⁷ The optimal mechanism can be implemented through a put option on the firm’s value that has an attached digital option such that over some range of firm values, the firm’s insiders are long the option and outside investors are short the option, whereas for all other firm values, insiders are short the option and outside investors are long. This mechanism works as follows. Firm insiders are asked to report the likelihood of success of their additional R&D investment, and are also asked to provide “insurance” to investors against the possibility that the firm’s R&D fails to achieve relatively high cash flows, i.e., a put option. The amount of insurance that insiders provide is larger if the firm reports a higher probability of success. The mechanism thus deters insiders from misrepresenting their R&D as having very probable high cash flows, while it (partially) protects investors against the firm’s failure to realize high R&D cash flows.

However, 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. Through this mechanism, investors are provided a stronger assurance of a relatively high upside, while insiders are provided stronger protection against the downside.⁸ Potential underinvestment in R&D is therefore avoided both by ensuring that insiders are not deterred by a high possibility of failure, and investors are not deterred by a low probability of high payoffs. We view this arrangement as intermediated finance because the binding precommitment and coordination in the optimal mechanism may not be sustainable in a market setting.

These options function as a form of bilateral insurance between investors and insiders,

⁷The government or a third-party entity such as an exchange could play the role of this intermediary.

⁸Although we do not have risk aversion in our model, this mechanism has an interesting interpretation in terms of encouraging risk-averse entrepreneurs to invest in R&D.

enabling them to protect each other against undesirable outcomes, thus allowing firms to make welfare-enhancing R&D investments. While some existing contracts suggest the idea of failure insurance for entrepreneurs, a novel normative aspect of our mechanism design is the put option sold by insiders to investors, as we discuss below. In terms of implementation, we relate these options to several recently proposed biopharma innovations such as FDA swaps and hedges (see Philipson (2015) and Jørring et al. (2017)) and “phase 2 development insurance”. Our analysis reveals the potential benefits of coordinating mechanisms between firms and investors to induce precommitment in R&D financing.

While we focus on R&D-intensive firms, our analysis also has broader implications for other industries where the probability of success is low, but the payoff conditional on success is high, and projects involve considerable technical expertise that makes risk shifting difficult to detect. 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. We introduce our model in Section 3. Section 4 contains the analysis of direct market financing, as well as a discussion of extensions to this analysis. Section 5 contains the analysis of the mechanism design, and we conclude in Section 6.

2 Related Literature

Our framework is related to the vast literature on optimal capital structure theory. 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 the way various frictions 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), Fluck (1998), Bolton, Chen, and Wang (2014), and Abel (2014), among others, propose theories of optimal capital structure based on the role of frictions stemming from

asymmetric information, agency problems, and tax distortions. For reviews, see Harris and Raviv (1991), Frank and Goyal (2005), and Myers (2001). In part, this literature has focused on the so-called pecking order of securities used to raise financing, with Myers and Majluf (1984) showing that equity is a last resort.⁹ More recent papers, like Fulghieri, Garcia, and Hackbarth (2015), have derived conditions under which this pecking order is reversed.¹⁰

While we also examine the optimal capital structure in the presence of asymmetric information and agency problems, we show how these frictions interact with the unique features of R&D-intensive firms to deliver different predictions about optimal capital structure, even within the well-known tradeoff between the risk shifting cost of debt and its tax benefit. Our analysis relative to this literature has two key distinguishing features. First, the expensing of R&D reduces the tax shield attributable to debt. Second, the risk shifting technology available to the firm is such that as the firm's risk-shifting ability increases, the agency cost of debt increases and the expected value of the tax shield decreases. A sufficiently high risk shifting ability leads to the cost of debt exceeding its benefit. In other words, risk shifting and the expensing of R&D for taxes can explain the heavy reliance on equity in R&D-intensive firms. Beyond this, we also explain why R&D-intensive may hold large cash balances and prefer using cash to either debt or equity, based on their concerns about signaling their R&D success to their competitors.

Our framework is also related to the theoretical literature on 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-intensive firms. While their focus is on the allocation of property rights and contracts in such firms, we focus on the optimal financing of R&D. Bhattacharya and Chiesa (1995) examine the R&D-intensive firm's choice between bank and market financing. In contrast, we examine how an intermediary, in *conjunction* with market

⁹Other papers that have explored the optimal choice of security in a setting of pure adverse selection related to asymmetric information include Brennan and Kraus (1987) and Nachman and Noe (1994).

¹⁰Another related paper is Halov and Heider (2011), which theoretically and empirically argues that asymmetric information about the risk of investments can lead to equity being preferred to debt in the pecking order.

financing, can reduce informational frictions, and hence increase R&D financing. Gertner, Gibbons, and Scharfstein (1988) develop a model in which the firm’s capital structure signals proprietary R&D information to product-market competitors. In contrast, the capital structure equilibrium in our model is pooling, so it does not play a signaling role.

Our contribution is thus related to Nanda and Rhodes-Kropf (2016), who show that “financing risk”—a forecast of limited future funding—disproportionately affects innovative ventures with the greatest option values. They propose that highly innovative technologies may need “hot” financial markets to be adequately funded. We take an alternative theoretical approach to this R&D funding gap, and derive a mechanism that mitigates it, regardless of market conditions.¹¹ This connects our framework 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).

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 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 $l \in (0, 1)$. Thus, absent liquidation of these personal assets, all financing needed for R&D must be raised from external financiers. All securities are raised in a competitive capital market, so the expected return for all investors who provide financing to the firm is zero.

¹¹Another related paper is Myers and Read (2014), who 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.

Conditional on having an R&D project at $t = 0$, the firm needs ωR 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 ωR 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 ωR 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. The corporate tax rate is $\tau \in (0, 1)$.

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 $x_L > R[1 + \omega]$. 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

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

and

$$\int_0^{x_L} x[1 - \tau] dL + \Gamma_c = R[1 - \tau] + \omega R\tau, \quad (2)$$

where

$$\Gamma_c \equiv \tau \left\{ \int_0^{R[1+\omega]} x dL + \int_{R[1+\omega]}^{x_L} R[1 + \omega] dL \right\}, \quad (3)$$

$\varepsilon > 0$ is an arbitrarily small positive scalar, and Γ_c is the tax shield associated with expensing R&D (the entire $R[1 + \omega]$) when the payoff distribution is L . The idea is that, with a good result in the first stage, 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 (given by (2)).¹²

If, and only if, the firm invested ωR at $t = 1$ will it have an opportunity to learn whether the outcome of the initial R&D is good or bad at $t = 2$. If it does not invest ωR 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 $\Delta R > 0$ 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 ΔR 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. If the firm has the cash to invest R and ΔR in R&D but chooses not to do so, at $t = 2$, the cash will be kept idle until $t = 3$ if the firm is sound. If it is unsound, it will abscond with the cash. All three distributions— L , H , and J —have associated continuous density functions that are strictly positive over their supports.

¹²For the case of drug development in biopharma firms, this is consistent with the empirical evidence of Grabowski and Vernon (1990).

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 and the capital structure of the firm. The firm chooses between debt and equity for its capital structure at $t = 0$; both debt and equity investors' claims are paid off at $t = 3$. 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 decisions are made by the firm's owners, while all other decisions are made by a manager, who privately observes at $t = 1$ whether a worthwhile R&D project is available, and then privately observes whether the first-stage R&D produced a good or a bad outcome at $t = 2$. Thus, it is the manager who decides whether to invest ωR 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. We assume that the manager makes all decisions in the best interests of the initial owners.

This specification of decision control seems natural. The initial owners (insiders) make the important strategic decisions about raising financing and capital structure. 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: adverse selection about R&D viability, asymmetric information about the upside potential of R&D, and risk-shifting.

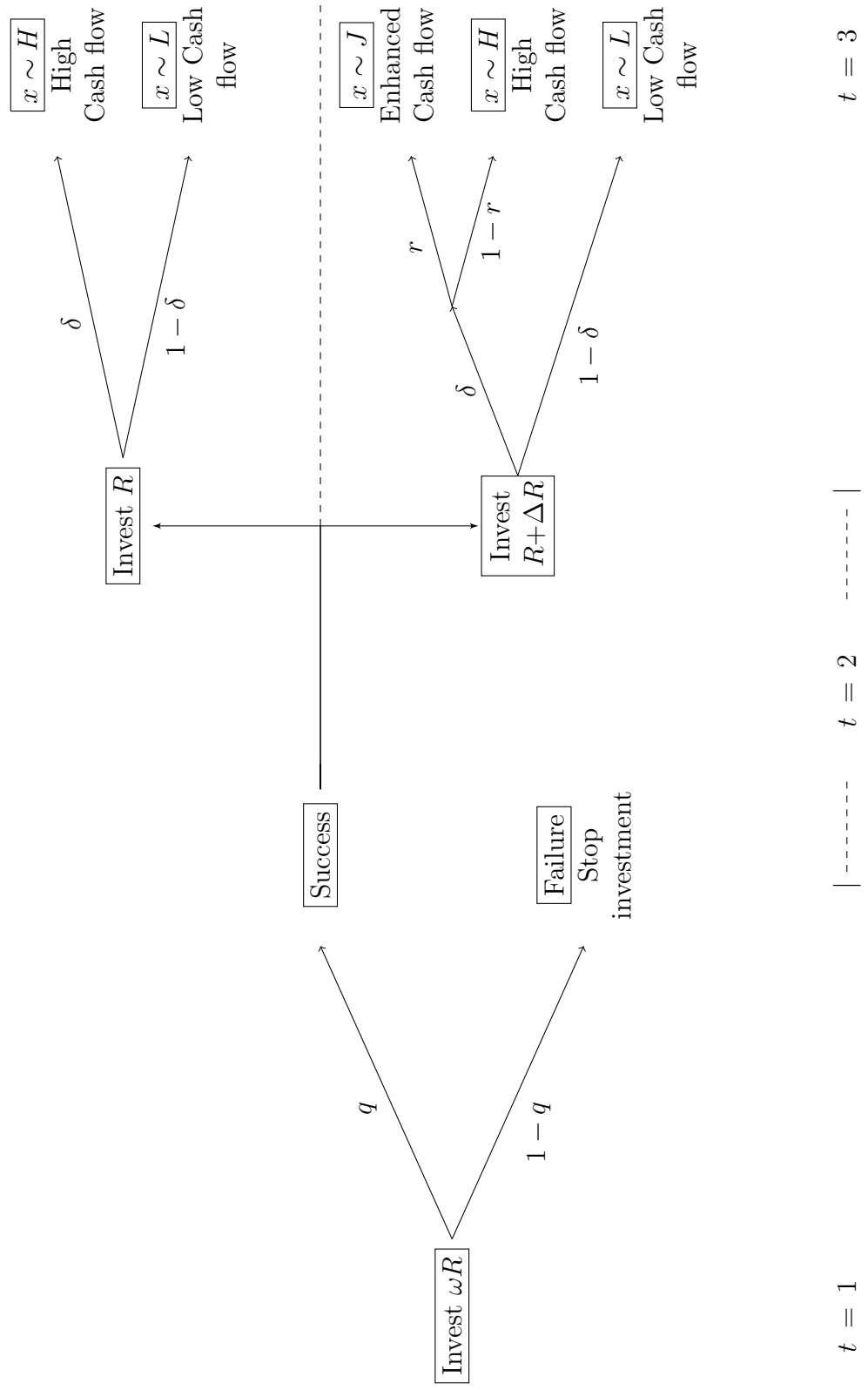


Figure 1: Summary of R&D Investment Timing (Absent Competitive Entry)

Adverse Selection: 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.

Asymmetric Information about R&D Upside Potential: The second informational friction is that, within the set of sound firms, there is unobservable 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).

“Buying Risk”: The Risk-shifting Opportunity: After securities are issued, the manager (on behalf of the initial shareholders) can unobservably change the riskiness of the R&D payoff distributions at $t = 2$. We assume that the manager can increase the measure of the support of L , H , as well as J by 2ν , where $\nu > 0$ is finite. That is, the manager can choose $\nu \in [0, \nu_m] \subset \mathbb{R}$ such that the lower end point of the support of the distribution decreases by ν and the upper end point increases by ν , with the following property being satisfied:

$$\begin{aligned}
\int_{-\nu}^{x_L+\nu} x dL - \int_0^{x_L} x dL &= \int_{x_L-\nu}^{x_H+\nu} x dH - \int_{x_L}^{x_H} x dH \\
&= \int_{x_H-\nu}^{x_J+\nu} x dH - \int_{x_H}^{x_J} x dH \\
&= 0
\end{aligned} \tag{4}$$

If the manager chooses to increase risk like this, he must do it for all three distributions.

However, to “buy” this additional risk, the manager must be willing to accept a pointwise

reduction of $m = \kappa\nu$, $\kappa \in (0, 1)$, in the realized value of the payoff under each of the three distributions, which yields a first-order-stochastic dominance shift of m to the left for each distribution. That is, for any chosen $\nu \in [0, \nu_m] \subset \mathbb{R}_+$, we have

$$\begin{aligned}
\int_0^{x_L} x dL - \int_{-\nu-m}^{x_L+\nu-m} x dL &= \int_{x_L}^{x_H} x dH - \int_{x_L-\nu-m}^{x_H+\nu-m} x dH \\
&= \int_{x_H}^{x_J} x dJ - \int_{x_H-\nu-m}^{x_J+\nu-m} x dJ \\
&= m = \kappa\nu
\end{aligned} \tag{5}$$

Given (4) and (5), it is clear that risk-shifting is inefficient—it leads to a lower total firm value. To capture the intuitive idea that higher cash flows permit more risk-shifting, we assume that ν_m is a function of x_H , with $\partial\nu_m/\partial x_H > 0$. In other words, when the upper endpoint of the high cash flow distribution is higher, it is easier for the firm to engage in (ex ante undetectable) risk shifting.

As the subsequent analysis will show, the manager has no incentive to engage in risk shifting when the firm has no leverage. However, with leverage, inefficient risk-shifting arises because the manager can increase the value of the initial owners' equity by doing so. The risk shifting involves increasing the variance of R&D payoffs, which is a classical risk-shifting strategy. Such flexibility for the manager has been modeled in many contexts previously. Jensen and Meckling (1976) introduced it in the context of capital structure, as we do here. Aumann and Perles (1965) discuss it in the context of the “variational problem” in which an agent who is rewarded on the basis of the realization of a (non-negative) random variable can select any distribution for the random variable, subject only to a restriction that the mean of the random variable does not exceed an exogenous constant. Makarov and Plantin (2015) examine this in the context of risk shifting by agents who are willing to take large risks to maximize expected compensation.

We believe that such risk shifting is especially important in R&D-intensive firms because three features of R&D make it very difficult to detect and prevent it through monitoring and

contracting. First, R&D has long gestation periods, so bondholders may be unable to observe in a timely manner signals that inform them that risk has been increased. Second, most R&D is very technical, and managers tend to have specialized expertise that bondholders and other stakeholders lack. This may make it difficult for bondholders to ascertain the precise riskiness of the project even when signals are available, because these signals are hard to interpret. And third, R&D has a low success probability anyway, so a shift to riskier R&D with an even lower success probability may be hard to catch.

3.3 Taxes

Any investment in R&D must be expensed for tax purposes and thus provides a tax shield. Similarly, all debt repayments are treated as tax deductible.

3.4 The Firm's Second-Stage Investment Decision

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

It is convenient to define the following:

$$\mu_H \equiv \int_{x_L}^{x_H} x dH, \quad \mu_L \equiv \int_0^{x_L} x dL, \quad (6)$$

and

$$\bar{G} \equiv \delta\mu_H[1 - \tau] + [1 - \delta]\mu_L[1 - \tau], \quad (7)$$

where \bar{G} is the after-tax expected value of the R&D in the good state (without competitive

entry). Further,

$$\Gamma_n \equiv \delta\tau R[1 + \omega] + [1 - \delta]\tau \left\{ \int_{R[1+\omega]}^{x_L} R[1 + \omega] dL + \int_0^{R[1+\omega]} x dL \right\} \quad (8)$$

is the expected value of the tax shield provided by the expensing of the R&D in the good state with no competitive entry.

We further make the following assumptions:

$$\bar{q} [\bar{G} + \Gamma_n] < R[1 - \tau] + \omega R\tau, \quad (9)$$

$$\omega R < \underline{q} [\bar{G} + \Gamma_n - R[1 - \tau] - \omega R\tau]. \quad (10)$$

Note that $\bar{q} [\bar{G} + \Gamma_n]$ is the expected value of investing R in the second stage. If R is kept idle, then the cash flow is R and ωR can be treated as a tax-deductible R&D expense. Thus, the after-tax cash flow is the right-hand side of (10). Condition (9) 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, and (10) says that the expected value of the option to invest R in R&D in the second stage exceeds the investment ωR in R&D in the first stage for any q .

3.5 The Effect of Competitive Entry

Competitive entry has two effects on R&D profitability. First, if a competitor enters at $t = 0$ and also invests ωR , then the first-stage R&D will yield a good outcome (success) with probability \underline{q} . Since competitive entry at $t = 0$ reduces the probability of R&D success to \underline{q} 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 $t = 2$ to the firm that invested ωR at $t = 1$ becomes arbitrarily

small (see (2))).

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.¹³ To ensure that a competitor will indeed wish to do this, we assume:

$$s \left[\mu_L [1 - \tau] + \int_0^R x\tau dL + \int_R^{x_L} R\tau dL \right] \geq R. \quad (11)$$

The left-hand side of (11) is the after-tax cash flow to a new entrant (who did not invest ωR at $t = 1$) from investing R at $t = 2$ (taking into account the probability that the firm is sound), and the right-hand side is the investment R . The intuition is that the upside potential of the R&D is high enough to make the investment positive-NPV for a potential competitor to enter, even if unsound firms are operating in the marketplace.

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.

3.6 Timeline of Events

Figure 2 summarizes the timeline of events and clarifies the actions of the players, as well as who knows what and when. Note that formally this is a game in which the informed firm moves first with its financing decision, and the uninformed investors move next. As *Figure 2*

¹³For 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. 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 (e.g. Grabowski (2007) and Thakor and Lo (2016)).

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 R&D-intensive firms.

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 ωR 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 element is the possibility of competitive entry. This delivers our result that firms will carry excess cash.

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. Absent this friction, the excess cash decision would be irrelevant in the sense that (sound) firms would perceive no cost to raising external financing and would be willing to raise any *ad hoc* amount of financing at any time. The ability to undertake a value-enhancing R&D investment ΔR 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. As discussed earlier, the manager's ability to engage in risk shifting is particularly relevant in the context of R&D-intensive firms. The nature of R&D can be altered in subtle—and undetectable—ways ex post without changing the basic purpose of the R&D or violating any bond covenants.

The final feature is taxes, which create a debt tax shield and provide the most familiar reason for using debt. But the fact that R&D can be immediately expensed means that R&D-intensive firms also have large *non-debt* tax shields, which affects the capital structure decision (e.g. DeAngelo and Masulis (1980)). The combination of taxes (including tax shields from R&D expensing) and risk shifting deliver our capital structure result.

$t = 0$	$t = 1$	$t = 2$	$t = 3$
<ul style="list-style-type: none"> • The firm’s insiders know whether the firm is “sound” or “unsound”, but investors do not. Others believe probability is s that the firm is sound. • A sound firm needs ωR for initial R&D investment at $t = 1$ and R for later investment at $t = 2$. • Firm raises financing from debt, equity, or a mix • The firm’s initial owners (insiders) could also liquidate personal assets Λ at a cost as an alternative to capital market financing. 	<ul style="list-style-type: none"> • Manager privately observes whether a worthwhile R&D project is available. • Manager decides whether to invest ωR in an R&D project (if there is a worthwhile one). 	<ul style="list-style-type: none"> • 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). Manager privately observes results. • $q = \bar{q}$ with no competitive entry, and $q = \underline{q} < \bar{q}$ with competitive entry. • The firm may raise additional financing from debt, equity, or a mix, which could convey information about B or G to competitors. • With G, firm invests R at $t = 1$. May also invest additional ΔR. • With B, firm ceases further investment. • The manager has the option to unobservably add risk to the R&D payoff distributions. 	<ul style="list-style-type: none"> • Final R&D payoff x is observed. • If firm invested R at $t = 2$, then $x \sim H$ with probability δ and $x \sim L$ with probability $1 - \delta$. • If firm also invested additional ΔR at $t = 2$, then high cash-flow realization (which happens with probability δ) 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

We assume that the deadweight cost of liquidating personal assets makes it impossible for insiders to raise *all* of the financing through personal-asset liquidation.

4 Analysis

We now analyze the model's implications. The initial owners of the firm decide at $t = 0$: (1) how much financing to raise; and (2) whether to raise financing with a mix of debt and equity, just debt, or just equity. 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 ωR in initial R&D. At $t = 2$, he will have to determine whether to invest R for further R&D, and also whether to undetectably engage in risk-shifting. The manager makes these decisions to maximize the wealth of the firm's initial owners.

4.1 Definition of Equilibrium

We now define the equilibrium concept we use. This is a game in which the informed manager moves first by raising capital, and the uninformed investors respond by pricing the securities.

Equilibrium: The competitive sequential equilibrium is one in which the informed manager makes decisions to maximize the expected wealth of the firm's initial owners. The equilibrium is: (i) a pair of strategies $\{I, C\}$ chosen by the manager at $t = 1$, where I is the total financing raised for R&D, and C is the capital structure (mix of debt and outside equity in the financing); (ii) investors' best response in terms of the pricing of the firm's securities at $t = 1$, conditional on their priors about whether the firm is sound, the information disclosed, and the probability β they attach to the manager engaging in risk-shifting at $t = 2$; (iii) the manager's strategy at $t = 2$ about whether to raise additional financing, how

much additional investment to make in R&D, and whether to engage in risk shifting, after observing whether competitive entry has occurred, with the manager's actual probability of risk shifting being β , the probability in the investors' belief at $t = 0$; and (iv) a belief revision process for investors whereby all beliefs are revised according to Bayes Rule when the manager plays his equilibrium strategies, and an out-of-equilibrium belief that the firm is unsound if the manager plays some other strategy.

4.2 Financing Amount and Excess Cash

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 ωR 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 faces a tradeoff. On the one hand, 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. We know that at $t = 2$, if additional financing is raised, it will alert the firm's competitors that the first-stage R&D (for a sound firm) was successful.¹⁴ Competitive entry at that point in time would reduce the margins of the project—something the firm would like to avoid. On the other hand, the signaling of R&D success in this manner will lower the adverse selection costs of raising financing.

Overall, since the R&D has high payoffs conditional on success, the cost of reducing the project's margins is greater than the reduction in adverse selection costs from raising financing at a later date. 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, and its capital raising is consequently less informative. That is, it is rational for the firm to reveal information at $t = 0$, *before* it knows how the first-period R&D will fare. In other words, it

¹⁴Even though there is a positive probability that the firm raising financing is unsound, the high upside potential of the project makes it rational for a competitor to enter into the marketplace. This is ensured by condition (11).

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.

4.3 The Debt-Equity Choice

Next we consider whether the firm will use debt or equity or some mix of the two to raise financing at $t = 0$.

4.3.1 Equity Financing

Consider first equity. It is clear that no risk-shifting will occur at $t = 2$ if the firm is all-equity-financed, so we can set $\beta = 0$ for this analysis. Let f be the fraction of ownership that the initial owners sell to investors of the sound firm in order to raise $[1 + \omega]R$, and let $d \in \{i, n\}$ be the firm's decision d to either issue (i) or not issue (n) securities to raise financing. That is, assume initially that ΔR is not raised. The initial owners of the sound firm solve the following maximization problem:

$$\max_d [1 - f] \Omega(\xi), \quad (12)$$

subject to:

$$\hat{s}f[\Omega] = [1 + \omega]R, \quad (13)$$

$$\begin{aligned} \Omega \equiv & \bar{q}[1 - \theta] [\bar{G} + \Gamma_n] + [1 - \bar{q}][1 - \theta] [R[1 - \tau] + \omega R\tau], \\ & + \underline{q}\theta [\mu_L[1 - \tau] + \Gamma_c] + [1 - \underline{q}]\theta [R[1 - \tau] + \omega R\tau] \end{aligned} \quad (14)$$

and

$$f \in [0, 1], \quad (15)$$

where Γ_c is defined in (3) and Γ_n is defined in (8). If no financing is raised, $[1 - f]\Omega$ in (12) is zero. So $d = i$ if, given (13), (14), and (15), the objective function in (12) is strictly positive.

This maximization can be understood as follows. (12) is given by the initial owners maximizing their share of the total firm value Ω , when their post-financing ownership share is reduced to $[1 - f]$. Equation (13) is the outside investors' equilibrium pricing constraint, where \hat{s} is the investors' posterior belief that the firm is sound after observing the firm's capital raising. Finally, (14) is the total firm value. If no competitive entry occurs (probability $1 - \theta$), 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 $\bar{G} + \Gamma_n$, where Γ_n is the value of the R&D tax shield in this state. If the first-stage R&D does not succeed (probability $1 - \bar{q}$), cash R sits idle. We assume it will be treated as income and taxed, but the ωR investment made earlier will be treated as an expense that generates a tax shield of $\tau\omega R$. This explains the first two term in the braces in (14). For the third term, if competitive entry occurs (probability θ), then the first-stage R&D success probability drops to \underline{q} , and the firm's value is $\mu_L[1 - \tau]$ plus the tax shield Γ_c associated with a payoff distribution of L (which occurs with competitive entry). Finally, in this case with competitive entry (probability θ), if the first-stage R&D does not succeed (probability $1 - \underline{q}$), cash R sits idle, so the value is $R[1 - \tau] + \omega R\tau$, as explained earlier. This explains the fourth term in the braces in (14).

Consider now the firm's incentive to raise the financing ΔR . We assume that, evaluated at \bar{r} , the prior belief about r , the payoff-enhancement R&D investment has negative NPV, i.e.,

$$\bar{q}\delta [\bar{r} [\mu_J - \mu_H]] < \Delta R, \quad (16)$$

where

$$\mu_J = \int_{x_H}^{x_J} x dJ, \quad (17)$$

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

Proposition 2: *There exists a sequential equilibrium where all firms avoid raising financing*

ΔR for R&D payoff enhancement. If a firm chooses to raise this financing, investors believe it is unsound with probability 1. Under the condition that a sound firm with $r = r_b$ would not raise financing ΔR if identified as a firm with $r = r_a$, this sequential equilibrium also satisfies the universal divinity condition of Banks and Sobel (1987).

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.¹⁵

4.3.2 Debt Financing

Now consider debt financing. Let F be the face value of debt that must be repaid at $t = 3$. We begin by proving some preliminary results.

Lemma 1: *For any $F > 0$, the manager will engage in the maximum risk shifting at $t = 2$, choosing $\nu = \nu_{max}$.*

The intuition is that, given the R&D payoff distribution, debt is risky in this model for any $F > 0$. With risky debt, the value of the call option represented by equity increases monotonically with risk.¹⁶ Our next result is about the impact of R&D expensing on the debt tax shield.

Lemma 2: *The tax shield benefit of debt is smaller when R&D is treated as a tax-deductible expense than when it is not, and, holding F fixed, the tax shield benefit of debt is smaller when the tax-deductible R&D expense is higher.*

¹⁵This sequential equilibrium is not unique. For example, another sequential equilibrium is one in which firms with $r > \hat{r}$ pool in raising financing and firms with $r < \hat{r}$ do not raise financing. However, these alternative equilibria simply change the market benchmark for determining the reservation utilities of firms participating in the mechanism design in Section 5. The main point is that none of these market financing equilibria are perfectly separating, in that there will still be viable R&D that is not funded, which opens the door to a role for intermediary-assisted mechanism design.

¹⁶We believe that the assumption the even debt financing in relatively small amounts will be risky in R&D-intensive firms is realistic. The unique features of R&D-intensive firms that we discussed earlier imply that issuing riskless debt is likely to be infeasible for these firms.

The reason for this in our model is that there is a set of states (with positive probability measure) in which the R&D payoff is smaller than the investment, i.e., R&D is risky. In these states, the debt tax shield has no value because no taxable income is left after R&D is expensed. Absent this expensing of R&D for tax purposes, the measure of the set of states in which debt provides a tax shield is larger.¹⁷

It is convenient to now define some terms:

$$A_1 \equiv \int_{x_L - [1-\kappa]\nu_m}^{x_H + [1-\kappa]\nu_m} \{(x - F) [1 - \tau] + [1 + \omega]R\tau\} dH, \quad (18)$$

$$A_2 \equiv \int_F^{F+[1+\omega]R} [x - F] dL + \int_{F+[1+\omega]R}^{x_L + [1-\kappa]\nu_m} \{[x - F - [1 + \omega]R] [1 - \tau] + [1 + \omega]R\} dL, \quad (19)$$

$$A_3 \equiv \int_{-[1-\kappa]\nu_m}^F x dL + \int_F^{x_L + [1-\kappa]\nu_m} F dL. \quad (20)$$

Here A_1 is the after-tax cash flows to shareholders when the payoff distribution is H , A_2 is the after-tax cash flow when the distribution is L , and A_3 is the expected payoff to the bondholders when the payoff distribution is L .¹⁸ The maximization program of the initial owners of the firm can be written as:

$$\max_d \Omega_D \quad (21)$$

$$\begin{aligned} \Omega_D \equiv & [1 - \theta] \bar{q} \left\{ \delta A_1 + [1 - \delta] \left\{ \int_{-[1-\kappa]\nu_m}^F [0] dL + A_2 \right\} \right\} \\ & + [1 - \theta] [1 - \bar{q}] [0] + [1 - \underline{q}] \theta [0] \\ & + \underline{q} \theta \left\{ A_2 + \int_{-[1-\kappa]\nu_m}^F [0] dL \right\} \end{aligned} \quad (22)$$

¹⁷DeAngelo and Masulis (1980) were the first to note that non-debt tax shields can reduce the value of debt tax shields. The empirical evidence on this is mixed; see Eckbo (2011).

¹⁸The support of L (with risk shifting) in A_3 includes negative values of x . The idea is that for $x < F$, the firm is bankrupt and belongs to the bondholders. Therefore, the bondholders must absorb the cost of liquidating the firm. The value from selling whatever the firm has is exceeded by the liquidation cost. This is an assumption of mathematical convenience.

$$\begin{aligned}
& \hat{s} \{ [1 - \theta] \bar{q} [\delta F + [1 - \delta] [F[1 - L(F)] + A_3] + [1 - \bar{q}] [1 - \theta] R] \} \\
& + \hat{s} \{ \underline{q} \theta [F[1 - L(F)] + A_3] + [1 - \underline{q}] \theta R \} \\
& = [1 + \omega] R
\end{aligned} \tag{23}$$

This maximization program can be understood as follows. The wealth of the sound firm's initial shareholders, Ω_D , is the total value of the firm minus what the firm owes to the bondholders—this is given by (22), and maximizing it is the objective function in (21). The firm will choose $d = i$ whenever $\Omega_D > 0$. What the firm owes to the bondholders is determined by the competitive equilibrium pricing constraint (23), and it includes the posterior belief \hat{s} that the firm is sound. Now, Ω_D in (22) is the sum of two parts. The first part 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 $1 - \theta$. The second part pertains to the value if there is competitive entry, and the probability of success in this case is \underline{q} . The probability of competitive entry is θ .

In writing expressions for A_1 and A_2 that are included in (22), it is recognized that the firm will engage in risk shifting. Moreover, R&D is treated as a tax-deductible expense *before* interest expense is deducted. Consider A_1 in (18). Over the entire support of H , $x > F$, so the firm's initial owners are able to get the entire tax shield associated with expensing R&D, $[1 + \omega]R\tau$. Now consider A_2 in (19). The support of L is such that debt is riskless only over a subset of that support. For $x \in [F, F + (1 + \omega)R]$, the firm pays no taxes due to the shield provided by the expensing of the R&D. For $x \in [F + [1 + \omega]R, x_L + [1 - \kappa]\nu_m]$, the firm's initial owners are able to capture fully the tax shield associated with R&D expensing.

4.4 Optimal Capital Structure

We now examine the firm's choice of debt versus equity at $t = 0$. To do this, we need to define notation.

First, denote by Γ_R the expected tax shield created by R&D expensing when the firm

uses debt financing:

$$\Gamma_R = [1 - \theta]\bar{q}\Gamma_n + [1 - \theta][1 - \bar{q}]\omega R\tau + [1 - \underline{q}]\theta\omega R\tau + \underline{q}\theta\Gamma_c, \quad (24)$$

and let Γ_F be the expected tax shield created by debt:

$$\Gamma_F = \tau \left\{ [1 - \theta]\bar{q}[\delta F + [1 - \delta]\varphi(F, [1 + \omega]R)] + \underline{q}\theta\varphi(F, [1 + \omega]R) \right\}, \quad (25)$$

where

$$\varphi(F, [1 + \omega]R) \equiv \int_{[1 + \omega]R}^F x dL + F[1 - L(F)]. \quad (26)$$

In (26), we note that (22) implies that $F > [\hat{s}(\xi)]^{-1}[1 + \omega]R$, so given the expensing of R&D, there is no debt tax shield until $x > [1 + \omega]R$.

An interesting aspect of risk shifting is that as the firm's ability to shift risk increases, there are two effects: the value of the debt tax shield decreases and the agency cost of debt increases. That is, a greater ex post ability to shift risk leads to a lower marginal value of debt as well as a higher marginal cost of debt. This is captured in our next result.

Proposition 3: *Assuming the density function associated with L is non-decreasing and x_L is sufficiently large relative to ν_m , an increase in ν_m leads to a decrease in the value of the debt tax shield, Γ_F , and an increase in the cost of debt as reflected in the expected loss in firm value due to risk shifting.*

Note that the reduction in firm value due to risk shifting only occurs when the firm invests R in R&D at $t = 2$, i.e., when the outcome of the first-stage R&D is good; otherwise R sits idly by on the firm's balance sheet. The probability of the firm investing R in R&D at $t = 2$ is $[1 - \theta]\bar{q} + \underline{q}\theta$. Thus, the expected reduction in firm value due to risk shifting is:

$$\mathcal{L} \equiv [1 - \tau] \left\{ [1 - \theta]\bar{q} + \underline{q}\theta \right\} \kappa\nu_m \quad (27)$$

The effects described in Proposition 3 are shown in *Figure 3*. This has an important implication for the firm’s capital structure, as reflected in Proposition 4.

Proposition 4: *Given the sufficiency condition in Proposition 4, there exists a ν_m^* such that, for all $\nu_m \geq \nu_m^*$, large enough such that the competitive sequential equilibrium involves an all-equity capital structure in which: (i) the firm raises $R[1 + \omega]$ at $t = 1$ entirely from (outside) equity; (ii) investors price the equity using Bayes Rule to revise their prior beliefs that the firm is sound after observing the equity issue, and also assume that the probability of risk-shifting by the firm is zero; and (iii) the manager does not engage in risk shifting. No capital is raised at $t = 2$. Any firm that raises capital different from $R[1 + \omega]$ at $t = 1$, raises capital at $t = 2$, or chooses a different capital structure is viewed as unsound with probability one by investors.*

This proposition describes a pooling sequential equilibrium. The unsound firm always mimics the capital structure of the sound firm because choosing any other capital structure would reveal its type almost surely. Consequently, a separating signaling equilibrium is precluded and investors price firms expecting sound and unsound firms to pool together.¹⁹

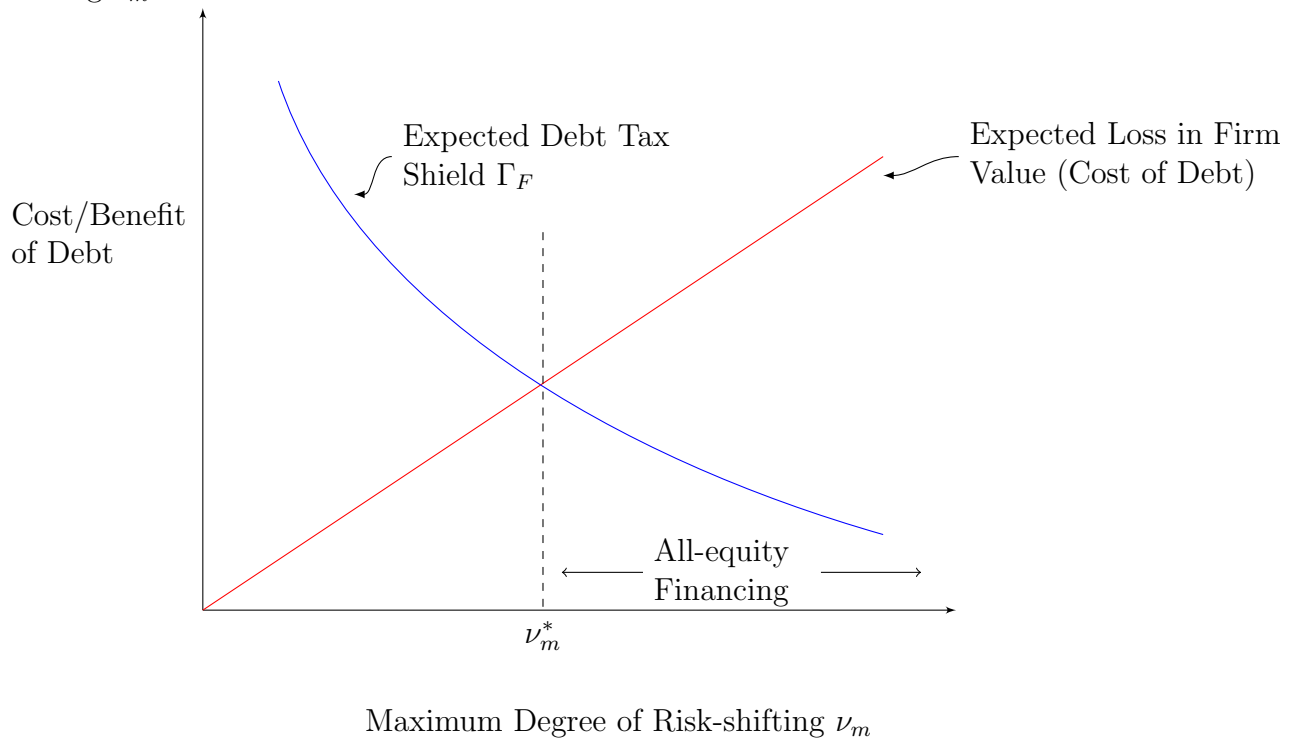
The result that there is a strict preference for either debt or equity in the capital structure—all debt if $\nu_m < \nu_m^*$ and all equity if $\nu_m \geq \nu_m^*$ —is striking. The reason is that when the maximal risk shifting is relatively low, the benefit of the debt tax shield is high and the agency cost of debt is low. So debt dominates equity. The more relevant case for our purposes is when the maximal risk shifting is relatively high, in which case the value of the debt tax shield is low and the cost of debt is high, so equity dominates debt. This effect is depicted in *Figure 3*.

This result should be contrasted with the usual capital structure result that relies on a tradeoff between the agency cost of debt which increases with the amount of debt and the

¹⁹For separation to occur, as in Ross (1977) for example, there should be a firm-type-dependent tradeoff between the benefit of choosing a given strategy (market value impact) and the future cost. The unsound firm’s valuation benefit from choosing the sound firm’s capital structure is the same as that for the sound firm, but it bears no future cost. Hence, it always pays for the unsound firm to “hide in the crowd”.

Figure 3: The Cost and Benefit of Debt as Functions of Risk Shifting

This figure depicts the cost and benefit of debt as functions of the maximum possible risk shifting ν_m for a fixed F .



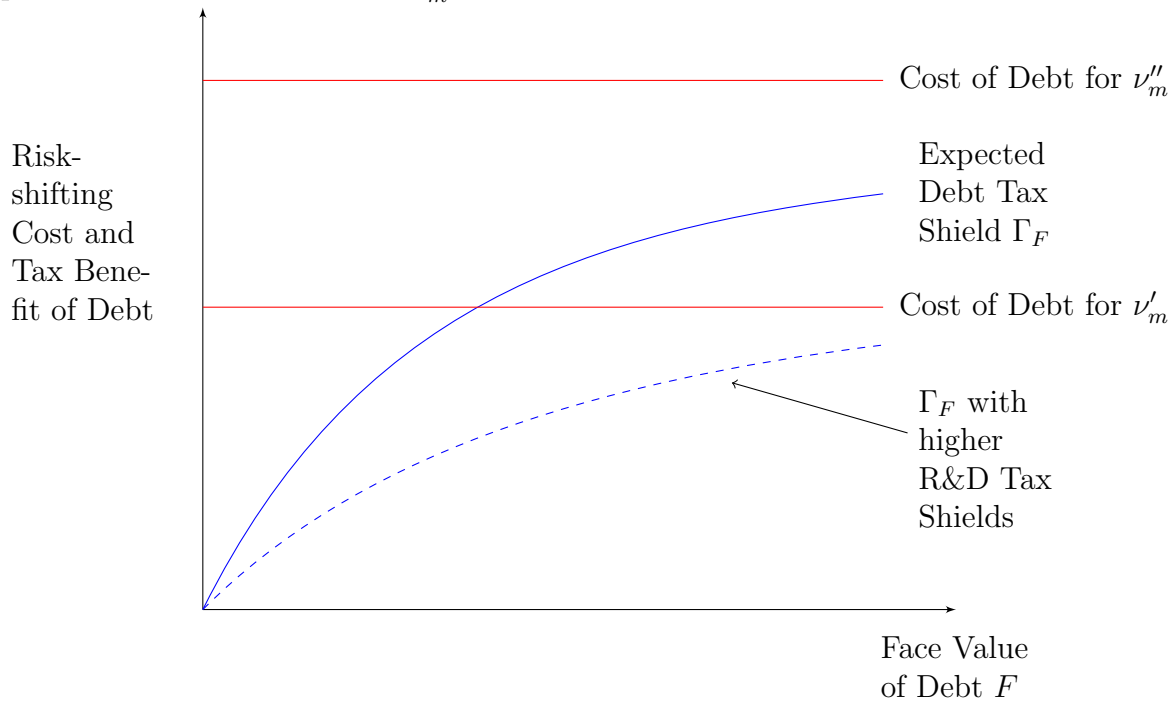
debt tax shield that also increases with the amount of debt, leading to an interior capital structure with debt and equity. In our model, the agency cost of debt arises for *any* $F > 0$ and it is invariant to the amount of debt, for a given ν_m . These effects are illustrated in *Figure 4*. From (25) we see that the expected debt tax shield Γ_F is increasing and concave in F for any ν_m . For a $\nu'_m < \nu_m^*$, there is some value of F at which Γ_F equals \mathcal{L} , the agency cost of debt—this value of F is given by the intersection of the Γ_F curve and the ν'_m line. For levels of debt F above this value, the value of the expected tax shield Γ_F is greater than the risk-shifting cost of debt ν'_m , and therefore the firm will choose to maximize the amount of debt that it holds. In contrast, for a higher risk-shifting ability $\nu''_m > \nu_m^*$, there is *no* value of F at which Γ_F equals the cost of debt. In this case, the risk-shifting cost of debt is always greater than the expected debt tax shield benefit of debt, and the firm will choose an all-equity capital structure. A key observation is that R&D tax shields, created by the expensing of R&D, reduce the value of the expected debt tax shields by reducing Γ_F for every value of F . This is depicted by the dashed concave tax-shield curve in the figure, which shows that a firm with greater R&D expenditures (and thus lower Γ_F) is less likely to prefer debt—such a firm would need to have a relatively low ability to risk-shift (lower ν_m) in order to have a preference for debt.

The combination of a tax rate τ low enough and a reduction in mean cash flow (with maximum risk shifting) $\kappa\nu_m$ high enough represents a sufficiency condition for equity to dominate debt. When $\kappa\nu_m$ is high, the expected loss in firm value due to risk shifting is also high. When τ is low, so is the debt tax shield. High levels of R&D expenditures further reduce the value of the debt tax shield.

The inequality $\nu_m \geq \nu_m^*$ is more likely to be satisfied for R&D-intensive firms than for other firms. First, as mentioned earlier, risk shifting is much easier to do but more difficult to detect in R&D—researchers can always reorient the R&D towards riskier bets with higher payoffs conditional on success without making the research seem visibly different, due to their technical expertise which outsiders lack. Thus, ν_m , which is larger when there is more

Figure 4: The Cost and Benefit of Debt as Functions of Debt Repayment F

This figure depicts the cost and benefit of debt as functions of F for various fixed values of maximum risk shifting, ν_m . The blue curve Γ_F represents the expected debt tax shield. The dashed blue curve shows the effect that additional R&D tax shields have on the expected debt tax shield. The red horizontal lines represent the risk-shifting cost of debt, which is constant for any given level of maximum risk shifting ν_m . The figure represents two possible levels of ν_m , where $\nu'_m < \nu_m^* < \nu''_m$. A strict preference for equity occurs for ν'_m , while a strict preference for debt occurs for ν''_m .



risk shifting, will be bigger in R&D-intensive firms. Note that the high upside of R&D also plays a role here—since ν_m is increasing in x_H , the high upside of R&D also contributes to the ease of risk shifting and the optimality of equity. Second, by Lemma 3, the expected debt tax shield Γ_F is smaller in R&D-intensive firms due to the tax-deductibility of R&D expenses.

An important caveat to this result is that we have assumed that the firm has no assets in place. With tangible assets in place, some debt enters the R&D-intensive firm’s capital structure, as we show below.

4.5 Extensions

In this section, we discuss a number of possible extensions of the model related to how R&D-intensive firms operate, and how these may affect our conclusions.

4.5.1 Pledgeable Assets-in-place or Cash Reserves

Suppose that the firm has P in pledgeable assets in place at $t = 0$. We now examine how this will change the analysis. Our next result shows that the firm in this case will issue an amount P in debt, but no more. Thus, the firm will issue debt up to the amount of pledgeable assets that it has in place and potentially maintain a mixed capital structure of debt and equity. This is summarized in the following Corollary.

Corollary 1: *An R&D-intensive firm will issue P in debt and raise the rest of its financing, $R[1 + \omega] - P$, from equity at $t = 0$*

The intuition is as follows. As long as the firm’s debt is limited to P , it is riskless (from the perspective of an investor) and hence does not induce any risk shifting by the firm. To take advantage of the positive debt tax shield, the firm thus issues debt up to P . Any debt above P is risky and will trigger the maximal risk shifting, as shown in the previous analysis.

One empirical implication of this result is that most of the cross-sectional variation in the

leverage ratios of R&D-intensive firms will be explained by the cross-sectional variation in their pledgeable assets. This pattern seems to hold in practice when examining the difference between certain types of R&D-intensive firms, for example pharmaceutical (“pharma”) and biotechnology (“biotech”) firms, in terms of their capital structures. Pharma firms tend to have greater amounts of assets in place 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, which has empirical support (see Thakor et al. (2017)).

4.5.2 Portfolio of Projects

In our model, the R&D project is a single project. In practice, firms may have portfolios of projects. 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 “mega-fund” by Fagnan et al. (2013) and Fernandez et al. (2012). A second benefit 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.

4.5.3 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, ΔR . A natural question that arises is whether it is possible to avoid this pooling outcome through signaling via debt as in Ross (1977)?

In our model, however, debt signaling does not eliminate the pooling with respect to the R&D-enhancing investment. 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 risk-shifting.²⁰ Thus, the single-crossing property does not hold. In the subsequent analysis, we explore a possible resolution to the pooling outcome of the R&D-enhancement.

4.5.4 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, R&D-intensive firms like biopharma firms also use 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.

Green (1984) showed that appropriately-designed convertible debt can mitigate risk-shifting moral hazard, emphasizing that this will only happen if the option to convert their debt to equity is exercised by the convertible holders only in a subset of the “upper-tail” cash flow states. In our model, these conditions are satisfied. Convertible holders will convert only when $x > F$. The set of states represented by $x \leq F$ can be divided into two subsets: $S_1 \equiv \{x \mid x \leq [1 + \omega]R\}$ and $S_2 \equiv \{x \mid x \in ([1 + \omega]R, F]\}$. In S_1 , convertible holders will not convert, but debt provides no tax shield benefit; all of the tax benefit comes from R&D expensing. In S_2 , there is a tax benefit of debt, but its expected value is $\tau \{[1 - \theta]\bar{q}[1 - \delta] + \underline{q}\theta\} \int_{[1+\omega]R}^F x dL$ (see (24)-(26)). The reason for this expression is that in states in which the firm does not invest in second-stage R&D, its payoff is only R , so all of the tax benefit comes from R&D expensing, and none from debt. So while convertible debt may reduce risk shifting, its tax shield advantage will be small if the R&D financing need is large (so that $x_L - [1 + \omega]R$ is small) and δ is relatively high.

It should also be noted that convertible debt, like debt and equity, will not solve the problem of non-investment in the R&D-enhancement ΔR . Indeed, to the extent that it is not

²⁰Note 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 $t = 0$.

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 address this in Section 5.

5 Financial Intermediation Mechanism

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, under some conditions, equity ends up at the top. That is, we return to our base case where the conditions of Proposition 4 are satisfied, so the firm is all-equity financed. However, there is still a friction that is not resolved by market financing—no firm will choose to invest ΔR to enhance the R&D payoff distribution from H to J , even though such an investment would be valuable for some firms.²¹ This raises the question of whether there is a mechanism beyond straight market financing that may improve outcomes.

To explore this, we introduce a financial intermediary that can, unlike the pure market financing case, make binding precommitments, get firms to do the same, and is not constrained to debt and equity. We thus view this mechanism as an intermediary-assisted approach that is used in conjunction with equity financing raised from the market.

5.1 Mechanism Design Framework

We approach this problem using the standard mechanism-design framework (e.g. see Myerson (1979)). The intermediary acts as an arbitrator that asks each firm to directly and truthfully report its r to the intermediary at $t = 0$. Based on the report, the intermediary awards the firm an allocation from a pre-determined menu of allocations that is designed to induce truthful reporting, i.e., achieve incentive compatibility (IC). The IC problem here is that a

²¹One 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.

low- r firm benefits (raises cheaper financing) from masquerading as a high- r firm, as we will formally verify shortly. So any general menu must be of the form $\{\mathcal{F}(r), \wp(r), \Re(r), \pi(r)\}$, where, contingent on a report of r , the firm: (1) receives financing terms of $\mathcal{F}(r)$ when it raises financing; (2) has a “penalty” of $\wp(r)$ ex post that it must pay investors if its realized cash flow x is not above some threshold (which may itself depend on the reported r); (3) receives a potential reward $\Re(r)$ if the realized cash flow is below some other threshold in order to satisfy the firm’s participation constraint given the penalty $\wp(r)$; and (4) faces a probability $\pi(r)$ that it will be allowed to participated in the mechanism.

From standard arguments, it follows that the financing terms $\mathcal{F}(r)$ will be such that the cost of financing for the firm is decreasing in r . To achieve IC, $\wp(r)$ will have to be increasing in r , i.e., the firm will be punished more for a cash flow falling below a threshold if it reported a higher r . The only way for the firm to pay the penalty is through personal asset liquidation by insiders. Since this is dissipatively costly, insiders may be given a reward $\Re(r)$ in some states to offset some of this cost and ensure satisfaction of their participation constraint. The key is that $\Re(r)$ must be designed so as *not* to interfere with the truthful reporting incentives created by $\wp(r)$. Finally, $\pi(r)$ simply ensures that only firms that are better off with the mechanism than with pure market financing are allowed to participate.

In what follows, we show that a general scheme like this can be implemented with *options*. Specifically, the intermediary 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 . The digital option causes investors to be 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 ζ lies in the interval (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.

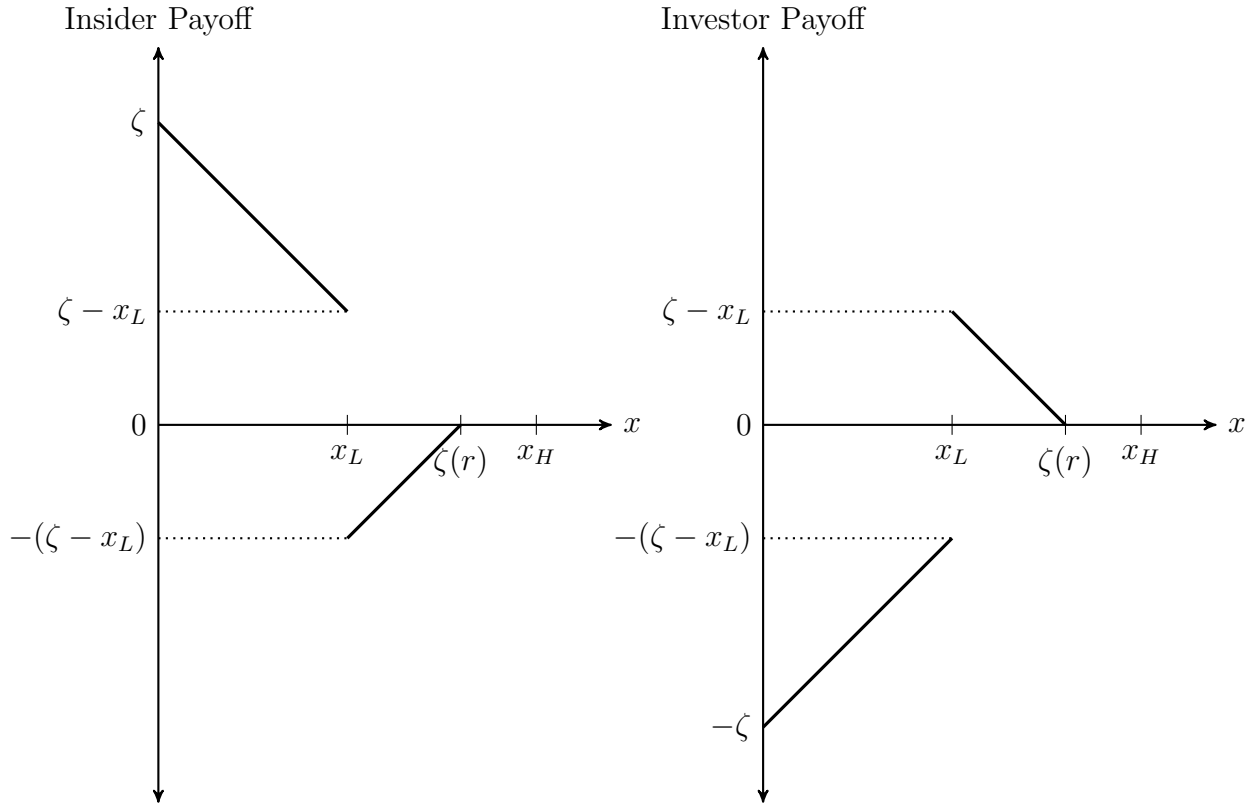


Figure 5: Mechanism Payoffs

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.

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 Λ at a cost. This requires a precommitment to the intermediary'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.

Let $\pi(r)$ be the probability that the intermediary 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 ΔR . Thus, the intermediary's mechanism Ψ can be described as:

$$\Psi : [r_a, r_b] \rightarrow \mathbb{R}_+ \times [0, 1]. \quad (28)$$

That is, the firm reports $r \in [r_a, r_b]$ to the intermediary, it is asked to create a put option with a strike price of $\zeta(r) \in \mathbb{R}_+$ (the positive real line), and is allowed to participate in the scheme with a probability of $\pi(r) \in [0, 1]$. Let $P_0(\tilde{r} | r)$ be the value of the put option when the firm reports \tilde{r} and its true parameter value is r , with $P_0(r | r) \equiv P_0(r)$. The investors then determine the fractional ownership f that the firm must sell in order to raise $[1 + \omega + \Delta] R$ at $t = 0$. We rely on the result of the previous section that equity dominates debt in the external financing pecking order, i.e., $\nu_m \geq \nu_m^*$ is assumed to hold. In what follows, we set the tax rate $\tau = 0$ to reduce notational clutter, since it plays no further role in the analysis.

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 intermediary'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:

$$[1 - f] \Omega(r), \quad (29)$$

subject to:²²

$$\Omega(r) = B_1 [\bar{G} + \delta r [\mu_J - \mu_H] + B_2 \mu_L + B_3 R], \quad (30)$$

$$\hat{s}f\Omega(r) = [1 + \omega + \Delta] R. \quad (31)$$

In the above, note that

$$B_1 \equiv \bar{q} [1 - \theta], \quad (32)$$

$$B_2 \equiv \underline{q}\theta, \quad (33)$$

$$B_3 \equiv [1 - \theta] [1 - \bar{q}] + \theta [1 - \underline{q}]. \quad (34)$$

5.2 Analysis of the Mechanism

We start with a result that the intermediary 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. Thus, by masquerading as a firm with a higher r , the firm can raise the needed financing by giving up a lower ownership share.

Under asymmetric information, the intermediary's problem can be expressed as that of

²²To obtain (30) below, note that

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

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 $\bar{G} \equiv \delta \mu_H + [1 - \delta] \mu_L$.

designing functions $\pi \in [0, 1]$ and ζ to solve:

$$\max \int_{r_a}^{r_b} \pi(r) \{ \Omega(r) + \alpha(r) - P_0(r)l^{-1} - \Omega^* \} z(r) dr, \quad (35)$$

subject to

$$\Omega(\tilde{r} | r) = B_1 [\bar{G} + \delta r [\mu_J - \mu_H] + B_2 \mu_L + B_3 R], \quad (36)$$

$$U(\tilde{r} | r) = \pi(\tilde{r}) \left\{ [1 - \tilde{f}] \Omega(\tilde{r} | r) - P_0(\tilde{r} | r) l^{-1} \right\}, \quad (37)$$

$$U(r) \geq U(\tilde{r} | r) \quad \forall r, \tilde{r} \in [r_a, r_b], \quad (38)$$

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

$$\hat{s} \left[\tilde{f} \Omega(r) + P_0(\tilde{r} | r) \right] = [1 + \omega + \Delta] R, \quad (39)$$

and $\Omega(r | r) \equiv \Omega(r)$, $U(r | r) \equiv U(r)$. Note that Ω^* is the total value of each firm that raises market financing. That is, the intermediary maximizes the incremental surplus from mechanism design relative to the market-financing outcome.

To understand the intermediary's mechanism design problem, note that in (35) the intermediary maximizes the expectation (taken with respect to r that the intermediary does not know) of the total value of the firm Ω , plus its social value α , minus the deadweight cost of the put option $P_0 l^{-1}$, minus the value Ω^* attainable with market financing. (36) is simply the firm value when the firm's true parameter is r and it reports \tilde{r} . (38) is the global incentive compatibility (IC) constraint, and (39) is the competitive capital market pricing constraint.

Henceforth, for simplicity, we shall assume that L , H , and J are all uniform. The value of the put option (assuming that $\zeta(r) > x_L$, something we will verify later as being associated

with the optimal solution) is given by:

$$P_0 = \left\{ B_1 \left[\delta [1 - r] \int_{x_L}^{\zeta} [\zeta - x] dH - [1 - \delta] \int_0^{x_L} [\zeta - x] dL \right] \right\} - \left\{ B_2 \int_0^{x_L} [\zeta - x] dL + B_3 [\zeta - R] \right\}. \quad (40)$$

Now,

$$\begin{aligned} \int_{x_L}^{\zeta} [\zeta - x] dH &= \int_{x_L}^{\zeta} \frac{\zeta - x}{x_H - x_L} dx \\ &= \frac{(\zeta - x_L)^2}{2[x_H - x_L]}. \end{aligned} \quad (41)$$

$$\begin{aligned} \int_0^{x_L} [\zeta - x] dL &= \int_0^{x_L} \frac{\zeta - x}{x_L} dx \\ &= \zeta - \mu_L. \end{aligned} \quad (42)$$

Substituting (41) and (42) in (40) gives:

$$P_0 = \frac{B_1 \delta [1 - r] [\zeta - x_L]^2}{2[x_H - x_L]} - B_1 [1 - \delta] [\zeta - \mu_L] - B_2 [\zeta - \mu_L] - B_3 [\zeta - R] \quad (43)$$

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

$$\inf_r \left\{ \frac{1 - r}{\phi(\xi)} \right\} > \frac{1 - l}{l} \quad (44)$$

and

$$-\frac{\partial \phi(r)}{\partial r} < \frac{l}{1 - l}. \quad (45)$$

These conditions guarantee 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 (38) as a local constraint.

Lemma 4: *The global IC constraint (38) is equivalent to:*

1. $U'(r) = \pi(r) \left[B_1 \delta [\mu_J - \mu_H] + \frac{[l^{-1}-1] \delta B_1 [\zeta - x]^2}{2[x_H - x_L]} \right]$ 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. (38) 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 (38) with conditions involving the first and second derivatives of U . This facilitates the subsequent analysis.

Lemma 5: *The regulator's mechanism design problem in (35)–(39) is equivalent to designing the functions π and ζ to maximize:*

$$\begin{aligned} & \int_{r_a}^{r_b} \pi(r) \left\{ \phi(r) \left[C_1 C_2 + C_1 [l^{-1} - 1] \left\{ \frac{[\zeta - x_L]^2}{2[x_H - x_L]} \right\} \right] \right\} z(r) dr \\ & + \int_{r_a}^{r_b} \pi(r) \left\{ \frac{[1 + \omega + \Delta] R}{\hat{s}} + \alpha(r) - \Omega(\xi^*) - P_0(r) \right\} z(r) dr \end{aligned} \quad (46)$$

where $C_1 \equiv B_1 \delta$ and $C_2 \equiv \mu_J - \mu_H$.

The following result characterizes the optimal mechanism.

Proposition 5: *The optimal mechanism involves:*

1. A put option strike price of

$$\zeta(r) = x_L + \frac{[x_H - x_L] \{ [B_1 [1 - \delta] + B_2 + B_3] \}}{B_1 \delta \{ [1 - r] - \phi(r) [l^{-1} - 1] \}}, \quad (47)$$

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.

$$\pi(r) = \begin{cases} 1 & \text{if } r \geq r^* \in [r_a, r_b] \\ 0 & \text{otherwise} \end{cases} \quad (48)$$

The intuition for this mechanism is as follows. Firms with lower values of r want to masquerade 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.

In addition, the digital option causes insiders to be long the put and investors short the put when $x < x_L$. Because the probability of $x < x_L$ does not depend on r , the probability of this digital option being exercised is the same for all firms regardless of r . So it reduces the probability of personal asset liquidation equally for all insiders. However, since the option strike price is higher for firms that report higher values of r , the reduction in the expected cost of personal asset liquidation is greater for the firms with higher values of r , a benefit to these firms that offsets their higher liability under the put option that is turned on when $x \in [x_L, x_H]$. The reduction in the expected cost of personal asset liquidation increases the expected utility of insiders. The probability of being allowed to participate in this mechanism is 1 as long as the mechanism enables the intermediary 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.²³

²³In this analysis we have taken the reservation utilities of the firms for participating in the mechanism

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 cash flows in the model: very low, intermediate, and very high. 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. 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 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 a high possibility of failure, and investors underinvesting due to suspicion of too low a probability of very high payoffs.

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 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.

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.²⁴ 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 as well as sound firms with a relatively low likelihood of achieving very high payoffs.

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 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 hedge”, which provides firms insurance against

²⁴It 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.

the failure of a drug to get FDA approval (see Philipson (2015) and Jørring et al. (2017) 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.

Overall, our mechanism highlights the value of credible precommitment to a coordinating mechanism between firm insiders and investors, which can increase R&D investments. As mentioned earlier, the intermediary in our mechanism could be any entity which plays an intermediation role, bringing firms and investors together, eliciting information about 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.²⁵ To the extent that existing contracts do not reflect the kind of bilateral exchange of insurance that our analysis says is 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 with intermediary assistance along the lines indicated here.

6 Conclusion

In this paper, we have developed a model of optimal investment and capital structure for R&D-intensive firms. We examine a setting with adverse selection and moral hazard in which 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 R&D-intensive

²⁵For 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.

firms.

We use this framework to explain various stylized facts about firms in this environment. First, these firms have lower leverage ratios than other firms, and they rely more 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 under conditions that prevail in R&D-intensive firms, 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 intermediary may design a mechanism that 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 beneficial 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 an intermediation-assisted 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 foundation for combining market financing and intermediation-assisted financing, as in the recently proposed alternative methods of financing biomedical innovation via “megafunds” (Fernandez, Stein, and Lo, 2012; Fagnan et al., 2013) which uses private-sector means to facilitate socially valuable R&D.

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Appendix

Proof of Proposition 1: Suppose this were not true. Then suppose the firm knows 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. Assuming that the firm is sound, this will make it publicly known that the first-stage R&D was successful. Of course, the probability that the firm is unsound is non-zero, but given (11), the disclosure that the first-stage R&D was successful will lead to competitive entry with probability one. Competitive entry at $t = 2$ means that the firm's expected project value will drop to

$$\int_0^{x_L} x dL - \int_R^{x_L} [x - R]\tau dL = R + \varepsilon, \quad (\text{A.1})$$

and thus the NPV of the investment to an entrant is ε . Since ε 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 Proposition 2: First, it is straightforward to see this is a Nash equilibrium—holding fixed the strategy of investors to price the firm that raised financing as if it is unsound, it is an optimal strategy for each sound firm to not raise financing. In equilibrium, then, no firm raises financing. Given this strategy, the optimal strategy for investors is to price the firm as if it is unsound. Given the out-of-equilibrium belief stipulated in the proposition, it is clear that the pooling Nash equilibrium is sequential, since each firm's equilibrium expected utility is higher than if it deviates from the equilibrium strategy. Further, since the unsound firm raises ΔR regardless of investors' beliefs about its type, whereas the sound firm with $r = r_b$ does not raise financing if identified as a sound firm with $r = r_a$, it is straightforward to verify that the set of beliefs of investors in response to the firm's deviation and raising of ΔR that induces the firm to deviate has larger measure for the unsound firm than for *any* sound firm. This is because if the sound firm with $r = r_b$ does not deviate, neither will any sound firm with $r < r_b$; in (16) note that $\partial \{\bar{q}\delta [\bar{r}[\mu_J - \mu_H]]\} / \partial r > 0$. Hence, the equilibrium is universally divine since investors will assign

a posterior belief that any firm raising financing is unsound with probability one. ■

Proof of Lemma 1: Using (18) and replacing ν_m by ν , we see that (defining h as the density function associated with H):

$$\begin{aligned} \frac{\partial A_1}{\partial \nu} &= \{[x_H + [1 - \kappa]\nu - F][1 - \tau] + [1 + \omega]R\tau\} [1 - \kappa]h \\ &\quad + \{[x_L - [1 - \kappa]\nu - F][1 - \tau] + [1 + \omega]R\tau\} [1 - \kappa]h \\ &> 0, \end{aligned} \tag{A.2}$$

since $h > 0$ everywhere on its support. Similarly, using (19) and replacing ν_m by ν , we see that (defining \hat{L} as the density function associated with L):

$$\begin{aligned} \frac{\partial A_2}{\partial \nu} &= \{[x_L + [1 - \kappa]\nu - F - [1 + \omega]R][1 - \tau] + [1 + \omega]R\} [1 - \kappa]\hat{L} \\ &> 0, \end{aligned} \tag{A.3}$$

since $\hat{L} > 0$ everywhere on its support. From (22), we see that Ω_D is strictly increasing in A_1 and $A_2 \forall F$. Thus, Ω_D is strictly increasing in ν for any F . ■

Proof of Lemma 2: From (26) we see that, holding F fixed,

$$\frac{\partial \varphi(F, [1 + \omega]R)}{\partial R} < 0, \tag{A.4}$$

which means that $\partial \Gamma_F / \partial R < 0$. Moreover, if R&D were not tax-deductible, then

$$\begin{aligned} \varphi(F, [1 + \omega]R) &\equiv \varphi(F) = \int_0^F x dL + F[1 - L(F)] \\ &> \int_{[1 + \omega]R}^F x dL + F[1 - L(F)], \end{aligned} \tag{A.5}$$

which means Γ_F is bigger if R&D is not a tax-deductible expense. ■

Proof of Proposition 3: Defining $\mathcal{L} \equiv [1 - \tau] \{[1 - \theta]\bar{q} + \underline{q}\theta\} \kappa \nu_m$, as subsequently in (27), it is clear that:

$$\frac{\partial \mathcal{L}}{\partial \nu_m} > 0. \quad (\text{A.6})$$

Now consider Γ_F defined in (25). We see that since

$$L(F) = \int_{-\nu_m[1+\kappa]}^F dL, \quad (\text{A.7})$$

we have:

$$\frac{\partial \mathcal{L}}{\partial \nu_m} = \hat{L}(-\nu_m[1 + \kappa]) [1 + \kappa]. \quad (\text{A.8})$$

Moreover,

$$\begin{aligned} \int_{[1+\omega]R}^F x dL &= \int_{-\nu_m[1+\kappa]}^{x_L + \nu[1-\kappa]} x dL - \int_{-\nu_m[1+\kappa]}^{[1+\omega]R} x dL - \int_F^{x_L + \nu_m[1-\kappa]} x dL \\ &= \mu_L - \kappa \nu_m - \int_{-\nu_m[1+\kappa]}^{[1+\omega]R} x dL - \int_F^{x_L + \nu_m[1-\kappa]} x dL. \end{aligned} \quad (\text{A.9})$$

Thus, defining $\varsigma_1 \equiv x_L + \nu_m[1 + \kappa]$ and $\varsigma_2 \equiv -\nu_m[1 + \kappa]$, we have:

$$\begin{aligned} \frac{\partial}{\partial \nu_m} \left[\int_{[1+\omega]R}^F x dL \right] &= -\nu_m - \left\{ [x_L + \nu_m[1 - \kappa]] \hat{L}(\varsigma_1) [1 - \kappa] - [-\nu_m[1 + \kappa]] \hat{L}(\varsigma_2) \right\} [-1 + \kappa] \\ &= -\nu_m - \left\{ [x_L[1 - \kappa]] \hat{L}(\varsigma_1) + \nu_m[1 - \kappa]^2 \hat{L}(\varsigma_1) - \nu_m[1 + \kappa]^2 \hat{L}(\varsigma_2) \right\}. \end{aligned} \quad (\text{A.10})$$

Using this and (25) we can now write:

$$\begin{aligned} \frac{\partial \Gamma_F}{\partial \nu_m} &= -\nu_m - \left\{ [x_L[1 - \kappa]] \hat{L}(\varsigma_1) + \nu_m[1 - \kappa]^2 \hat{L}(\varsigma_1) - \nu_m[1 + \kappa]^2 \hat{L}(\varsigma_2) \right\} - F \hat{L}(\varsigma_2) [1 + \kappa] \\ &= -\nu_m - \left\{ [x_L[1 - \kappa]] \hat{L}(\varsigma_1) + \nu_m[1 - \kappa]^2 \hat{L}(\varsigma_1) + F \hat{L}(\varsigma_2) [1 + \kappa] - \nu_m[1 + \kappa]^2 \hat{L}(\varsigma_2) \right\} \end{aligned} \quad (\text{A.11})$$

Given that \hat{L} is non-decreasing and $\varsigma_1 > \varsigma_2$, a sufficient condition for the expression in (A.11) to be negative is that:

$$x_L[1 - \kappa] + \nu_m[1 - \kappa]^2 > \nu_m[1 + \kappa]^2 \quad (\text{A.12})$$

It is clear that (A.12) holds if $x_L[1 - \kappa] > 4\kappa\nu_m$, i.e., if x_L is sufficiently large relative to ν_m . ■

Proof of Proposition 4: From Proposition 3, we know that Γ_F is decreasing in ν_m and \mathcal{L} is increasing in ν_m . Moreover, $\mathcal{L} = 0$ at $\nu_m = 0$ and increases linearly in an unbounded manner with ν_m . Thus, $\exists \nu_m^* \in \mathbb{R}_+$ (where \mathbb{R}_+ is the positive real line) such that $\Gamma_F > \mathcal{L} \forall \nu_m < \nu_m^*$ and $\Gamma_F \leq \mathcal{L} \forall \nu_m \geq \nu_m^*$. Thus, the sound firm's shareholders are better off with all-equity financing $\forall \nu_m \geq \nu_m^*$. Given this, there will be a pooling equilibrium in which all firms use an all-equity capital structure and investors' posterior belief $\hat{s} = s$, the prior belief that the firm is sound. With all equity, the manager does not engage in any risk shifting because doing this reduces the value of equity. Given the out-of-equilibrium belief stipulated in the proposition, the equilibrium is sequential. ■

Proof of Corollary 1: This follows in a straightforward manner from the discussion in the text. ■

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 f_i be an 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

$$[1 - f_2] \Omega(r_1) > [1 - f_1] \Omega(r_1) \quad (\text{A.13})$$

which follows since $f_1 > f_2$. Note that $f_1 > f_2$ follows from (31) and the fact that $\Omega(r)$ defined in (30) is strictly increasing in r and the right-hand side of (A.13) is a constant. Thus, the r_1 firm will misreport its type as r_2 . ■

Proof of Lemma 4: Substituting from (39) into (37), we can write (suppressing ξ as an argument of the functions):

$$\begin{aligned} U(r) &= \left[\Omega(r) - \frac{[1 + \omega + \Delta]}{\hat{s}} + P_0 - P_0 l^{-1} \right] \pi(r) \\ &= \pi(r) \left[\Omega(r) - \frac{[1 + \omega + \Delta] R}{\hat{s}} - [l^{-1} - 1] P_0 \right]. \end{aligned} \quad (\text{A.14})$$

We will first show that (38) implies parts 1 and 2 of the lemma. From (38) we have that $U(r | r) \geq U(\tilde{r} | r)$, so:

$$\begin{aligned}
& \pi(r) \left[\Omega(r) - \frac{[1 + \omega + \Delta] R}{\hat{s}} - [l^{-1} - 1] P_0(r) \right] \\
\geq & \pi(\tilde{r}) \left[\Omega(\tilde{r} | r) - \frac{[1 + \omega + \Delta] R}{\hat{s}} - [l^{-1} - 1] P_0(\tilde{r} | r) \right] \\
= & \pi(\tilde{r}) \left[\Omega(\tilde{r}) - \frac{[1 + \omega + \Delta] R}{\hat{s}(\tilde{r})} - [l^{-1} - 1] P_0(\tilde{r}) \right] + B_1(\tilde{\xi}) \delta r [\mu_J - \mu_H] \pi(\tilde{r}) \\
& - B_1(\tilde{\xi}) \delta \tilde{r} [\mu_J - \mu_H] \pi(\tilde{r}) + [l^{-1} - 1] B_1(\tilde{\xi}) \left[\frac{\delta [1 - r] [\zeta - x_L]^2}{2 [x_H - x_L]} \right] \pi(\tilde{r}) \\
& - [l^{-1} - 1] B_1(\tilde{\xi}) \left[\frac{\delta [1 - \tilde{r}] [\zeta - x_L]^2}{2 [x_H - x_L]} \right] \pi(\tilde{r}) \\
= & U(\tilde{r}) + B_1 \delta [r - \tilde{r}] \pi(\tilde{r}) \left[[\mu_J - \mu_H] + [l^{-1} - 1] \left\{ \frac{[\zeta - x_L]^2}{2 [x_H - x_L]} \right\} \right]. \tag{A.15}
\end{aligned}$$

Thus,

$$U(r) - U(\tilde{r}) \geq [r - \tilde{r}] N(\tilde{r}), \tag{A.16}$$

where

$$N(\tilde{r}) \equiv \pi(\tilde{r}) [1 - \kappa] B_1 \delta \left[[\mu_J - \mu_H] + [l^{-1} - 1] \left\{ \frac{[\zeta - x_L]^2}{2 [x_H - x_L]} \right\} \right]. \tag{A.17}$$

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

$$U(\tilde{r}) - U(r) \geq [\tilde{r} - r] N(r), \tag{A.18}$$

which implies

$$U(r) - U(\tilde{r}) \leq [r - \tilde{r}] N(r). \tag{A.19}$$

Combining (A.16) and (A.19) yields:

$$[r - \tilde{r}] N(\tilde{r}) \leq U(r) - U(\tilde{r}) \leq [r - \tilde{r}] N(r). \tag{A.20}$$

Inspection of (A.20) 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 $\tilde{r} \rightarrow r$ to write:

$$\lim_{\tilde{r} \rightarrow r} \frac{U(r) - U(\tilde{r})}{\tilde{r} - r} = U'(r) = N(r) > 0 \text{ almost everywhere.} \quad (\text{A.21})$$

Since $N(r)$ is non-decreasing, it follows that $U'' \geq 0$ almost everywhere. Thus we have shown that (38) implies parts 1 and 2 of the Lemma.

Next, we will show that parts 1 and 2 of the lemma imply (38). Note that

$$\begin{aligned} U(r | r) - U(\tilde{r} | r) &= U(r | r) - U(\tilde{r} | r) + [r - \tilde{r}] N(\tilde{r}) \\ &= \int_{\tilde{r}}^r U'(t | t) dt - [r - \tilde{r}] U'(r | \tilde{r}) \\ &\geq 0, \end{aligned} \quad (\text{A.22})$$

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:

$$\int_{r_a}^r U'(\tilde{r} | \tilde{r}) d\tilde{r} = \int_{r_a}^r N(\tilde{r}) d\tilde{r}, \quad (\text{A.23})$$

which means

$$\begin{aligned} U(r) - U(r_a) &= \int_{r_a}^r N(\tilde{r}) d\tilde{r} \\ \implies U(r) &= U(r_a) + \int_{r_a}^r N(\tilde{r}) d\tilde{r}. \end{aligned} \quad (\text{A.24})$$

Taking the expectation of (A.24) yields:

$$\begin{aligned}
\int_{r_a}^{r_b} U(r)z(r)dr &= U(r_a) + \int_{r_a}^{r_b} \left[\int_{r_a}^r N(t)dt \right] z(r)dr \\
&= U(r_a) + \int_{r_a}^{r_b} N(t) \left[\int_t^{r_b} z(r)dr \right] dt \\
&= U(r_a) + \int_{r_a}^{r_b} \phi(r)N(r)z(r)dr,
\end{aligned} \tag{A.25}$$

where $\phi(r) \equiv \frac{[1-Z(r)]}{z(r)}$. Now we know from (37) that

$$\pi(r) [\Omega(\xi, r) - P_0(r)l^{-1}] = U(r) + \pi(r)f\Omega(r). \tag{A.26}$$

Substituting in (A.26) for $f\Omega$ from (39) gives us:

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

Substituting (A.27) into (35) yields the objective function:

$$\int_{r_a}^{r_b} \left\{ U(r) + \pi(r) \left[\frac{[1 + \omega + \Delta]R}{\hat{s}} + \alpha(r) - \Omega(\xi^*) - P_0(r) \right] \right\} z(r)dr. \tag{A.28}$$

The arbitrator can give insiders of the lowest type ($r = r_a$) their expected utility with market financing. Let this expected utility be \bar{u}_a . Then set $U(r_a) = \bar{u}_a$ and substitute (A.25) in (A.28) above to get

$$\bar{u}_a + \int_{r_a}^{r_b} \left\{ \phi(r)N(r) + \pi(r) \left[\frac{[1 + \omega + \Delta]R}{\hat{s}} + \alpha(r) - \Omega(\xi^*) - P_0(r) \right] \right\} z(r)dr. \tag{A.29}$$

Now use (A.17) and write

$$N(r) = \pi(r)C_1 \left[C_2 + [l^{-1} - 1] \left\{ \frac{[\zeta - x_L]^2}{2[x_H - x_L]} \right\} \right], \tag{A.30}$$

so that the arbitrator's objective function (A.29) can be written as:

$$\bar{u}_a + \int_{r_a}^{r_b} \pi(r) \left\{ \phi(r) \left[C_1 C_2 + C_1 [l^{-1} - 1] \left\{ \frac{[\zeta - x_L]^2}{2[x_H - x_L]} \right\} \right] + \frac{[1 + \omega + \Delta] R}{\hat{s}} + \alpha(r) - \Omega(\xi^*) - P_0(r) \right\} z(r) dr. \quad (\text{A.31})$$

This completes the proof since maximizing (A.31) is equivalent to maximizing (46) because \bar{u}_a is a constant (i.e. independent of the mechanism design functions). ■

Proof of Proposition 5: Let us first prove (47). From optimal control theory, we know that the value function ζ that maximizes (A.31) is the one that involves maximizing the integral pointwise. Thus, the first-order condition for ζ is:

$$\begin{aligned} & \phi(r) [l^{-1} - 1] B_1 \delta [\zeta - x_L] [x_H - x_L]^{-1} \\ & - \left\{ B_1 \delta [1 - r] [\zeta - x_L] [x_H - x_L]^{-1} - B_1 [1 - \delta] - B_2 - B_3 \right\} = 0, \end{aligned} \quad (\text{A.32})$$

which yields (47) upon rearranging. The second-order condition is:

$$\phi(r) [l^{-1} - 1] B_1 \delta [x_H - x_L]^{-1} - B_1 \delta [1 - r] [x_H - x_L]^{-1} < 0, \quad (\text{A.33})$$

which requires

$$B_1 \delta [x_H - x_L]^{-1} \{ \phi(r) [l^{-1} - 1] - [1 - r] \} < 0, \quad (\text{A.34})$$

which holds since (45) tells us that

$$\frac{1 - r}{\phi(r)} > l^{-1} - 1. \quad (\text{A.35})$$

Moreover, $\partial \zeta / \partial r > 0$, also given (45). Inspection of (A.31) also reveals that the arbitrator will set $\pi = 1$ whenever the term multiplying $\pi(r)$ in (A.31) 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.

■