Optimal Financing for R&D-Intensive Firms*

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Abstract

We examine optimal financing for R&D-intensive firms. When firms raise external financing using equity, they underinvest in R&D. But when the feasible set of contracts is augmented to include more general payoff schemes, this underinvestment is reduced. We then use a mechanism design approach and show that such schemes can be implemented with options to attenuate R&D underinvestment. The mechanism combines equity with put options so that investors can insure firms against R&D failure and firms can insure investors against high R&D payoffs not being realized. Involving a financial intermediary to implement the mechanism improves welfare. This highlights a new role for financial intermediaries in using relationships with multiple firms to reduce welfare losses in market financing for these firms.

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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 observation that R&D is difficult to fund in a competitive market has a long tradition, dating back to Schumpeter (1942) and Arrow (1962). There is also empirical evidence of a "funding gap" that creates underinvestment in R&D (see Hall and Lerner (2010)). Consequently, many potentially transformative technologies are not being 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?

In this paper, we address this question from a financial contracting perspective. Because R&D outlays are typically large, firms need external financing, for which adverse selection is ever-present (see Myers and Majluf (1984)).[2] In addition, the riskiness of R&D cash flows—low success probabilities combined with high payoffs conditional on success—can deter firms from undertaking R&D.[3] While investors may be more willing than managers to bear these risks, they would need assurance that the high payoffs conditional on success will actually be realized, and that the high upside potential of the R&D is not overhyped by the firm seeking financing, a difficult task given the specialized knowledge inherent in R&D.

We provide an analysis of external R&D financing being raised by a firm that faces

[1]This funding gap exists for venture-backed as well as public firms (e.g. Nanda and Rhodes-Kropf (2016)). Brown, Fazzari, and Petersen (2009) empirically document a significant link between financing supply and R&D. Lerner, Shane, and Tsai (2003) show that biotechnology firms are more likely to fund R&D through potentially inefficient alliances during periods of limited public market financing. Thakor, Anaya, Zhang, Vilanilam, Siah, Wong, and Lo (2017) document that pharmaceutical and biotechnology companies have a significant systematic risk. 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, making the case for more innovative financing methods.

[2]DiMasi, Grabowski, and Hansen (2014) note that the development cost of a single new drug in the biopharmaceutical sector is estimated to be $2.6 billion.

[3]See DiMasi et al. (1991, 2013), Grabowski, Vernon, and DiMasi (2002), and Kerr and Nanda (2015). This can happen even with risk neutrality of decisionmakers if R&D failure causes the firm to incur financial distress costs or suffer inefficient asset liquidation. Moreover, managers may be diversified financially and risk neutral towards financial payoffs, but may bear undiversifiable employment risk that they may be averse to.

the frictions discussed above. We lay the groundwork for our analysis by first examining a market financing outcome setting. Because there are existing theories as well as empirical evidence that R&D-intensive firms rely largely on equity financing (e.g. Lerner, Shane, and Tsai (2003), Brown, Fazzari, and Petersen (2009), Fulghieri, Garcia, and Hackbarth (2020)) and have very low leverage (e.g. Bradley, Jarrell, and Kim (1984), Himmelberg and Petersen (1994), and Thakor and Lo (2022)), we start by assuming that the firm will prefer equity when its external financing is limited to standard debt and equity. However, standard external financing generates an outcome in which all firms underinvest in incremental payoff-enhancing R&D investments. We view the firms in our analysis as publicly-traded, R&D-intensive firms such as small biopharma companies engaged in early-stage research and exploration, for whom the underinvestment problem would be particularly acute, rather than firms in big pharma.[4]

The implications of our model are consistent with the empirically-documented underinvestment in R&D even by publicly-traded firms (e.g. Brown and Petersen (2011), Hall and Lerner (2010), Krieger, Li, and Papanikolaou (2022)). This underinvestment with market financing establishes a benchmark that sets the stage for the main intended contribution of the paper.

We then turn our attention to the more normative issue of whether the market financing outcome can be improved upon by adding a general scheme of rewards and penalties to the menu of market-traded contracts. We show the existence of schemes that can reduce underinvestment. The scheme may involve a *binding precommitment* from the firm's insiders to make costly ex post payouts from personal wealth. In this case, we also show that introducing a financial intermediary can improve welfare. The intermediary improves welfare by reducing the dissipative cost incurred by the firm's insiders in using a part of their illiquid personal wealth to make their payout. This shines new light on the potential role of financial

[4]Our analysis is also applicable to venture-backed firms to the extent that they raise debt and equity in the private markets—some of it through venture capital—and exhibit empirically-documented underinvestment in R&D. We also note that our conclusions regarding underinvestment hold for hybrid securities, such as convertibles.

intermediaries in reducing the welfare losses of market financing for firms using multiple-firm relationships. After establishing these results, we use a mechanism design approach to show how options can implement the reward and penalty scheme that attenuates underinvestment.

Introducing option contracts to supplement market financing enables us to examine improvements based largely on existing contracts, thus allowing us to focus our attention to mechanisms that may be feasibly implemented in practice. The mechanism involves extracting truthful reports from firms about their privately-known profitability of an additional R&D investment.[5] We show that 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 to "insure" investors against the R&D failing to achieve high cash flows, i.e., they offer investors a put option. The insurance that insiders provide is greater if the firm reports a higher success probability. 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, such insurance is costly for the insiders. To partially offset this cost, the mechanism also includes a put option offered by the investors to the insiders, which insures the insiders against very low cash flows. Investors are thus provided a stronger assurance of a relatively high upside, while insiders are provided stronger protection against the downside, and underinvestment in R&D is reduced. We then argue, as in the case with non-linear rewards and penalities, that a financial intermediary, used in conjunction with these options, can improve welfare.

These options function as bilateral insurance between investors and insiders, enabling them to protect each other against undesirable outcomes, thus allowing firms to make welfare-

[5]A third-party entity such as an exchange or a financial intermediary could elicit these reports.

enhancing R&D investments. We relate the options contracts that comprise the mechanism to existing and proposed contracts. Similar to the put option sold by investors to insiders in our mechanism, a variety of existing contracts involve failure insurance for entrepreneurs, such as "research and development insurance" that is offered for a range of industries such as manufacturing and drug development. The put option sold by insiders to investors in our mechanism in conjunction with equity financing is analogous to "putable common stock" that has been used by some firms.[6] Recently proposed contracts for the biopharma industry, like FDA swaps and hedges (Philipson (2015) and Jorring et al. (2017)), combine aspects of both types of option contracts. A novel aspect of our analysis is showing theoretically these options contracts can be combined through a digital (switching) option to resolve the R&D underinvestment problem.[7]

Our paper is connected to the venture capital (VC) contracting literature that examines control rights between financiers and entrepreneurs. Two key results in this literature are that staged financing is optimal because it preserves the abandonment option (Gompers (1995) and Cornelli and Yosha (2003)), and that debt and convertibles are optimal (Schmidt (2003) and Winton and Yerramilli (2008)). Our results are starkly different—while investment in our model is staged, financing is not and equity is used to raise external financing. The reason for this difference is that, as long as market financing is raised via equity, there is no conflict over the continuation decision in our model, whereas this conflict exists with debt.[8] Thus, our model applies primarily to firms where such conflicts are not first-order with outside equity, and where the non-verifiability of interim cash balances precludes contracts

[6]Putable common stock gives investors the option to sell their stock back to the firm. It was introduced in 1984 by investment banking firm Drexel Burnham Lambert, and has been used by firms such as Dreyer's Grand Ice Cream Holding Company. See Cantale and Russino (2006) and Chen and Kensinger (1988) for analyses of putable common stock.

[7]Our result that contracts with options are optimal in R&D is consistent with Lerner and Malmendier's (2010) observation that contracting difficulties in research activities can make it optimal to use contracts with termination options. However, their result is very different in the sense that it is a termination option for the financier that acts to deter cross-subsidization in research by the firm.

[8]Other papers have shown that staged financing itself can produce conflicts of interest and hold-ups (e.g. Admati and Pfleiferer (1994)) and give disproportionate bargaining power to the initial VC (Fluck, Garrison, and Myers (2006)).

with triggers based on interim state realizations.[9]

Our paper is related to the theoretical literature on incentives, decision-making, and contracts in R&D-intensive firms, e.g. Aghion and Tirole (1994), Bhattacharya and Chiesa (1995), and Gertner, Gibbons, and Scharfstein (1988). Our work also involves financing and contracting issues, but differs in terms of our focus on the juxtaposition of mechanism design with market financing to resolve informational frictions that generate R&D underinvestment. Our paper is related to Manso (2011), who shows that the optimal incentive contracts to motivate innovation within firms involve high tolerance for early failure and rewards for long-term success. While we do not examine optimal contracts to provide incentives for agents within firms to innovate, our analysis complements these papers in that we show how the firm can contract with investors in the financial market to ensure that it has the financial resources to be failure tolerant, i.e., not be insolvent when R&D fails. That is, our analysis highlights how contracting between the firm and its investors can facilitate optimal contracting within the firm to incentivize innovation. Our contribution is also related to Nanda and Rhodes-Kropf (2016), who show that "financing risk", e.g., a forecast of scarcer future funding, disproportionately affects innovative ventures with the greatest option values. They conclude that highly innovative technologies may need "hot" financial markets to be funded. While our analysis is consistent in that we also show how innovation may fail to be funded via market financing, we take a different approach by deriving a mechanism that mitigates the funding gap, regardless of market conditions.[10]

To summarize, we have three main results in the paper. First, we show that standard market financing with equity leads to underinvestment in R&D when there is asymmetric information about the upside potential of R&D. That is, an informational asymmetry that is

[9]Firms that are funded by multiple VCs that are not able to exercise control rights may be one example. Our model is also applicable to other types of venture-backed firms to the extent that they raise capital in the private markets—some of it through venture capital—and exhibit empirically-documented underinvestment in R&D.

[10]Another 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.

particularly germane to R&D contributes to underinvestment in R&D with equity. Second, a mechanism design approach that admits securities with arbitrary (non-linear) penalties and rewards improves on the market outcome and elevates R&D investment. This analysis generates a novel contract involving bilateral insurance that addresses both the high risk of failure to the innovating firm and the potential risk to investors that the very high payoffs that attracted them may never be realized. Under certain conditions, options can implement these general reward and punishment schemes. We also discuss the relationship of our mechanism to recent contracting innovations in biopharma. Third, due to the dissipative nature of penalties in these schemes, there is a welfare loss that can be reduced by using a financial intermediary. This highlights a new role for financial intermediaries—they can work with multiple firms seeking market financing and use these multiple relationships for achieving a reduction in the welfare losses of *market* financing for these firms.

We describe the setup of the base model in Section 2. Section 3 contains the preliminary analysis of capital market financing. Section 4 contains the main mechanism design analysis with discrete firm types and analyzes how an intermediary can improve welfare. Section 5 generalizes this to a continuum of types and shows how the scheme can be implemented with options. We conclude in Section 6. All proofs are in the Appendix.

2 The Model

2.1 Firms and Investment Decisions

Firms and Agents: There are two dates: $t = 1$ and $t = 2$. All agents are risk neutral and the riskless rate is zero. There are R&D-intensive firms, each with assets in place at the beginning, date $t = 1$, prior to raising external financing. These assets have a random value $\tilde{A}$ that is correlated with future R&D success in a manner to be made precise shortly. The initial owners of the firm (insiders) have personal assets (not part of the firm) that are illiquid at $t = 1$ and will deliver a payoff that is valued by the insiders as $\Lambda \in \mathbb{R}_+$ at $t = 2$ if held until $t = 2$. These assets, if liquidated at $t = 1$, can be used by the insiders to partially 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 any date, where $l \in (0, 1)$.[11] In other words, these illiquid assets are worth more to insiders if held until $t = 2$ than if converted to cash at any date. We assume that the deadweight cost of liquidation makes it impossible for insiders to raise *all* of the financing through personal-asset liquidation—i.e., $l\Lambda$ is not large enough to meet all of the firm's financing needs. Thus, absent personal asset liquidation, R&D financing must be raised from external financiers. Moreover, even if these assets are pledged for conversion into cash at $t = 2$, this pledge need not be honored by insiders without explicit monitoring by an intermediary like a bank.

We refer to the insiders as the "manager", who can be viewed as owner-managers in the spirit of founding CEOs. The firms are publicly traded and can issue securities in a competitive capital market, where the expected return for all investors is zero.

R&D Projects and Payoffs: Conditional on having an R&D project at $t = 1$, the firm needs $R > 0$ in capital at $t = 1$ to invest in R&D to develop a new idea, and do exploratory research, including clinical trials and obtaining FDA approval, purchasing equipment and hiring people for additional research and product development, larger-scale clinical trials, investing in downstream assets for product distribution, and so on. We will assume throughout that R is much larger than Λ, so even if all personal assets are liquidated, significant external financing will be required.

Let $\delta \in (0, 1)$ be the probability that investing R will produce a high cash flow distribution, i.e., the date $t = 2$ cash flow x will have a cumulative distribution function H with support $[x_L, x_H]$ and $x_L > R$) and a probability $1-\delta$ of achieving a low cash flow distribution

[11] These assets may include ownership in other smaller privately-held R&D-intensive firms which may be very illiquid, patents on products yet to be commercially developed, or other illiquid personal assets like household possessions or other durable goods that their owners value more than potential buyers. The source of illiquidity here is not asymmetric information about the value of the illiquid asset, but rather that the current owner of the asset is a higher-value user than others to whom the asset could be sold. In a sense, the interpretation here is similar to that related to the dissipative cost of collateral transfer in Besanko and Thakor (1987).

L with support $[0, x_L]$. The means of H and L are μ_H and μ_L, and we assume $R > \mu_L$. So we can view $x \sim H$ as success and $x \sim L$ as failure. The random value $\tilde{A}$ at $t = 2$ is correlated with R&D success. These assets could be viewed as R&D-related knowledge assets that can be used in additional research and development as well as downstream assets whose value is higher when R&D succeeds (see, e.g., Krieger, Li, and Thakor (2022)).[12] Conditional on $x > x_L$, the value of $\tilde{A}$ is determined by a state variable γ that has the distribution $\Pr(\gamma = \gamma_h) = r$ and $\Pr(\gamma = \gamma_l) = 1 - r$, so $\tilde{A} = A > 0$ when $\gamma = \gamma_h$ (with probability r) and $\tilde{A} = 0$ when $\gamma = \gamma_l$ (with probability $1 - r$), where $r \in [r_a, r_b] \subset [0, 1]$. Further, $\gamma = \gamma_l$ with probability 1 when $x \leq x_L$, so $\tilde{A} \equiv 0 \,\forall\, x \leq x_L$. Since $x > x_L$ with probability δ, this means that the unconditional probability of $\tilde{A} = A$ is δr. We assume that A is not a pledgeable cash flow when the firm invests $R[1 + \omega]$, i.e., its value is possessed by insiders but it cannot be contracted upon to provide any cash flow to outside investors. Assume that each firm's insiders knows the firm's r privately.

Let $\overline{G}$ be the expected value of the cash flow x produced by the R&D:

$$\overline{G} \equiv [1 - \delta] \int_0^{x_L} x \, dL + \delta \int_{x_L}^{x_H} x \, dH > R. \tag{1}$$

The assumption that $\overline{G} > R$ means that investing R at $t = 1$ is worthwhile even ignoring the value of assets in place. Further, the total value of the firm is:

$$\Omega(r) = \overline{G} + \delta r A. \tag{2}$$

R&D Enhancement: Finally, if the firm invests R at $t = 1$, it can also invest an additional $\triangle R > 0$ at $t = 1$, where $\triangle$ is a constant. This investment generates a probability $r \in [r_a, r_b]$

[12]Krieger, Li, and Thakor (2022) discuss and provide empirical evidence of such downstream assets in the context of biopharma, which they refer to as "commercialization capital". Examples of these assets may also include R&D knowledge that insiders have as a result of the exploration made possible by investing $R + \omega R$ that is patentable, but may or not not yet be patented. Patents can be granted early on in the development process, before the ultimate success of the R&D process is known. Success in the R&D process will make the patent the firm holds for the product more valuable.

that the high cash flow distribution can be enhanced from H to J, where J is distributed over the support $[x_H, x_J]$. That is, if $\triangle R$ is additionally invested in R&D at $t = 1$, then whenever $\gamma = \gamma_h$, the cash flow x will be distributed according to J, where J first-order-stochastically dominates H. In other words, conditional on investing $\triangle R$, the ex ante probability is δr that the distribution of x is J and $\delta[1 - r]$ that the distribution of x is H. We assume that there exists an $\hat{r} \in [r_a, r_b)$ such that the expected payoff enhancement from investing $\triangle R$, which is $\delta r[\mu_J - \mu_H]$, exceeds $\triangle R \; \forall \, r > \hat{r}$. Thus, there is at least a subset of values of r for which investing $\triangle R$ is efficient (positive NPV). This R&D-enhancement can be interpreted as the discovery of additional commercial applications of the R&D conditional on the R&D being successful (i.e. $x \sim H$).

For example, a given medicinal compound that is targeted for a particular disease may also have wider applications than initially considered, and these applications are only revealed with additional exploration. There are many examples of this. Listerine started out as an anti-septic to clean floors and treat gonorrhea before being developed and marketed as a mouthwash. Botox was originally approved for treatment of muscle spasms. After further research, it was discovered to have cosmetic applications in addition to being effective at treating migraines.

Restriction 1: We assume that

$$\overline{G} < R + \triangle R. \tag{3}$$

This condition means that while $\overline{G}$ exceeds R, it is less than $R + \triangle R$, so the higher investment cannot be supported without giving financiers a claim also on the firm's assets in place.

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

[Insert Figure 1 Here]

2.2 Firm's Financing Decisions

At $t = 1$, the manager determines how much external financing to raise and the capital structure of the firm. Financing is raised at $t = 1$, and financiers are paid off at $t = 2$. The firm can choose to invest either R or $R + \triangle R$.

There is asymmetric information about the value of the assets in place, but absent the investment $\triangle R$, there is symmetric information about the distribution of the cash flow x. Since the expected value of x exceeds R, the firm could issue equity with a claim only on this cash flow. That is, the external financiers would have no claim on $\tilde{A}$. There are a few different ways to implement this. One is project financing, wherein the R&D project is financed as a stand-alone asset, separate from the firm's other assets (e.g. Shah and Thakor (1987)). Another approach is organizationally simpler, wherein insiders can give themselves an exclusive claim on $\tilde{A}$ either as part of executive compensation or as repayment on a loan (outside of the model) to the firm made at the time of setting it up.

Consider now the firm's incentive to raise $\triangle R$ for the payoff-enhancement investment. We assume that, evaluated at $\overline{r}$, the prior belief about r, the payoff-enhancement R&D investment has negative NPV, but it has positive NPV for r high enough.

Restriction 2: The value of the assets in place is sufficiently large relative to the expected value enhancement from investing $\triangle R$:

$$\overline{G} < R\left[1 + \frac{A}{\mu_J - \mu_H}\right]. \tag{4}$$

This condition helps to ensure that with equity financing, in equilibrium firms will be unwilling to incur dilution costs.

2.3 Informational Frictions

The model has one main friction: asymmetric information about the upside potential of R&D.[13] Firms seeking financing are heterogeneous with respect to r—each firm's manager privately knows r at $t = 1$, but others do not know r at any date. It is common knowledge that r is distributed in the cross-section of firms over $[r_a, r_b]$ according to the probability density function z (with cumulative distribution function Z) with mean $\bar{r}$. Asymmetric information about r introduces the possibility that market financing may not resolve all informational problems, leaving room for mechanism design to play a role. Since r affects both the value of the assets in place created by investing R and the payoff enhancement created by $\triangle R$, there is asymmetric information regardless of whether $\triangle R$ is raised.

2.4 Mechanism Design

In the market financing case, we analyze the firm's capital raising using equity. With mechanism design, we permit a more general set of payoffs. Following Myerson (1979), mechanism design involves each firm being asked to truthfully and directly report its private information, and then being given financing with a contract whose terms are contingent on the firm's reported r. The report may simply be equivalent to choosing an element from a menu posted by investors, or it may be a report to a mechanism designer or an intermediary.

2.5 Financial Intermediary

In our analysis of market financing, we do not have an intermediary. However, when we examine mechanism design, we analyze how a financial intermediary could enhance welfare. This analysis looks at the combination of market financing with equity, (non-market) mechanism design, and an intermediary to coordinate the implementation of the mechanism.

[13] For simplicity, we assume no taxes. In an extension not included in the paper, we introduce taxes and show that this may lead to the firm using a small amount of debt, but will not change the need for mechanism design to attenuate underinvestment. We also discuss how introducing additional benefits of debt will not change this conclusion. These analyses are available upon request.

Specifically, we assume that, in line with the role of intermediaries as specialists in screening and monitoring, an intermediary can noisily detect whether a firm that has submitted a report of its type has reported truthfully. Thus, the presence of the intermediary facilitates satisfaction of non-mimicry constraints, although it does not eliminate misrepresentation incentives.

2.6 Timeline of Events and Equilibrium Concept

Figure 2 summarizes the timeline of events, the actions of the players, as well as who knows what and when. Formally this is a model in which the informed firm moves first with its financing decision, and the uninformed investors move next by pricing the securities.

[Insert Figure 2 Here]

With market financing, the equilibrium concept is a competitive Bayesian Perfect Nash Equilibrium (BPNE) in which the informed manager makes decisions to maximize the expected wealth of the firm's initial owners. Specifically, the informed manager moves first at $t = 1$ by choosing to raise financing, anticipating investors' reaction to the issuance. The investors observe the financing choice, revise their beliefs about the firm's type, and then price the securities competitively so that their expected return is zero. Investors' actions are consistent with the reaction anticipated by the manager. If the firm's choices are along the path of play, investors use Bayes Rule to revise their beliefs. If the firm chooses an action off the equilibrium path, there exists an out-of-equilibrium belief of investors such that a best response conditional on that belief induces the firm to not choose that out-of-equilibrium action.

With mechanism design, the firm's manager reports the firm's r at $t = 1$ and obtains a set of financing terms based on that report. The mechanism allows for a probability that the firm may be unable to participate in the mechanism for certain reports. In that case, the firm avails of market financing at $t = 1$.

3 Market Financing

It is well known that R&D-intensive firms rely heavily on equity when then raise external financing (e.g. Brown, Fazzari, and Petersen (2009)). Thus, for expositional parsimony, we simply assume that the firm relies only on equity for external market financing.[14] Our analysis of equity financing is intended to provide a benchmark for the mechanism design results.

Now let f be the fraction of ownership that the manager sells to investors to raise 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 $\triangle R$ is not raised. Investors who provide the funding have a claim only on the cash flow x. Recalling that $\overline{r} = \mathbb{E}[r]$ (prior belief about r), the manager solves:

$$\max_{d} [1 - f] \overline{G} + \delta r A, \tag{5}$$

subject to:

$$f\overline{G} = R, \tag{6}$$

and

$$f \in [0, 1], \tag{7}$$

If no financing is raised, the objective function in (5) is zero. So $d = i$ if, given (6), (9), and (7), the objective function in (5) is strictly positive.

We now have:

Proposition 1: *It is feasible for all firms to raise financing R with equity at $t = 1$ for their investment needs at $t = 1$. Assuming $R + \triangle R$ is sufficiently large and $r_a > 0$ is sufficiently small, all firms raising equity financing are pooled in equilibrium at the same valuation in the market, regardless of r, even when signaling with inside ownership is allowed. All firms raise R by issuing claims only against the cash flow x, and not the assets in place, $\tilde{A}$. No*

[14] An analysis that establishes sufficiency conditions for equity financing to be the optimal choice when the firm can choose between debt equity is available upon request.

firm raises $\triangle R$ in equilibrium (i.e. all firms raise only R), and any firm attempting to raise $\triangle R$ (off the equilibrium path) is believed by investors to have $r = r_a$ with probability one. This BPNE is an equilibrium that survives the D1 criterion of Cho and Sobel (1990).

Proposition 1 makes the following points. First, all firms are pooled in pricing when they raise equity. This is because it turns out to be inefficient for insiders to vary the amount of external financing they raise and thereby use (costly) equity retention by insiders as a signal—as in Leland and Pyle (1977). As the proof shows, the equity retention needed for incentive compatibility requires insiders to sell illiquid assets to finance inside ownership and this imposes too large a cost to induce the highest-r firm to signal. Second, with pooling, no firm raises $\triangle R$ in equilibrium, because doing so requires issuing claims against assets in place, causing insiders to suffer dilution costs.[15] The expected value of the assets in place, $\delta r A$, depends on the probability r, which the firm knows privately. By raising financing $\triangle R$ at a pooling price, firms with higher values of r suffer greater dilution. Whenever a firm deviates from the pooling equilibrium and raises $\triangle R$ in financing, investors have the most pessimistic belief about its type, and this belief survives the D1 criterion, which is a stronger refinement than the Intuitive Criterion (Cho and Kreps (1987)) and divinity (Banks and Sobel (1987)).

3.1 Discussion of the Possible Benefits of Debt

Our external financing analysis has neither the costs (e.g. risk shifting) nor the documented benefits of debt (e.g. debt tax shield). What would these features do? In supplemental analysis, we show that since R&D is a tax-deductible expense, the tax benefits of debt kick in only for income exceeding R&D investment, and will thus be small. Additionally, the maximum feasible debt will typically be below the level that triggers risk shifting. Thus a small amount of debt may be used in equilibrium, but our main analysis will be qualitatively

[15] That is, adverse selection, similar to that in Myers and Majluf (1984), is triggered when the firm attempts to raise $\triangle R$.

unaffected since market-based financing still leaves underinvestment in R&D.[16]

3.2 Discussion: Venture Capital

One might note that standard venture capital contracts may attenuate the underinvestment problem. However, the empirical evidence indicates that even venture-backed firms experience a funding gap for R&D investments (e.g. Nanda and Rhodes-Kropf (2016)). Moreover, staged financing itself can produce conflicts of interest and hold-up problems (e.g. Admati and Pfleiderer (1994)) and give disproportionate bargaining power to the initial VC.

Thus, even if it is possible for a VC to acquire the firm's private information about R&D profitability, this resolution will entail its own costs.[17] In that sense, the mechanism design approach analyzed in the next section can be viewed as a financial-innovation alternative to conventional VC financing or an expanded set of contracts VCs could use to overcome the early-stage R&D underinvestment problem that many small R&D-intensive firms, such as biotech firms, experience.

4 A More General Financing Mechanism with an Intermediary

Our analysis of market financing in the previous section provides conditions under which no firm chose to invest $\triangle R$, even though doing so would be valuable for some firms.[18] This raises the question: is there a mechanism beyond straight market financing that may improve outcomes?

[16] This analysis is available upon request.

[17] Specifically, if the VC cannot distinguish between the good and bad outcomes, then it will be unable to use contracts with control-transfer triggers based on interim cash flow realizations. This is likely to be a salient problem for R&D, which requires substantial specialized knowledge and technical expertise. This can diminish the value of using a VC in the first place.

[18] One could also interpret this enhancement as something that has a positive social externality that is not internalized in the NPV calculation for the firms. For example, this could be a drug that may have wider applications given further testing.

To explore this, we expand the feasible set of contracts to include more general contracts. We demonstrate that using such contracts as part of the optimal mechanism allows the residual information asymmetry problem to be resolved and underinvestment in R&D to be reduced. In particular, we show that the optimal mechanism that emerges is equity combined with a state-contingent payment for investors if the firm's cash flow is not high enough. The payment to investors may involve the insiders of the firm having to liquidate their illiquid assets. We will show that this may violate their participation constraint, and this can be be addressed with a payment from investors to insiders in states in which the firm's cash flow is very low, along with the introduction of a financial intermediary as a go-between.

4.1 Mechanism Design Framework

We analyze this problem using standard mechanism design (Myerson (1979)). The intermediary asks each firm to directly and truthfully report its r at $t = 1$. Based on the report, the intermediary awards the firm an allocation from a pre-determined menu designed to induce truthful reporting, i.e., achieve incentive compatibility (IC). The IC problem here is that a low-r firm benefits (raises cheaper financing) from masquerading as a high-r firm, as we will formally verify shortly. So an incentive compatible 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 $\wp(r)$ paid to investors ex post if its realized cash flow x is not above some threshold (which may itself depend on the reported r); (3) receives a 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 participate in the mechanism.

Equilibrium in Reporting Game: In the reporting game equilibrium: (i) each firm truthfully reports its r; (ii) conditional on the report, each firm receives an allocation $\{\mathcal{F}(r), \wp(r), \Re(r), \pi(r)\}$, such that investors earn zero expected return for each r; and (iii) firms for which $\pi(r) > 0$ participate in the mechanism, whereas those for which $\pi(r) = 0$ seek equity financing in the capital market.

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 the r that it reports.[19] To achieve incentive compatibility, $\wp(r)$ 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 rewarded $\Re(r)$ 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.

We provide a formal analysis of such a mechanism below for the simple case in which there are only two possible values of r. In Section 5, we analyze how such a scheme can be implemented with options when r lies in a continuum. Before doing so, however, we present the first best outcome when all firms raise and invest $\triangle R$ for the R&D payoff enhancement.

4.2 First Best

Let $\Omega(\triangle, r)$ be the total value of a firm whose parameter is r and it raises the additional financing $\triangle R$. Note that while the Ω the manager uses in his objective function depends only on the true r, f will depend only on the $\tilde{r}$ the manager chooses to report. Before stating the intermediary's problem, we describe the first-best solution when each firm's r is common knowledge, and investors price securities accordingly in a competitive market. Because of the deadweight loss associated with managers liquidating their own assets to cover the cost of making payments to investors in some sates, in the first best no firm provides a payment guarantee, and relies solely on equity financing with no underinvestment.

[19] This is along the envelope of costs with truthful reporting by all firms.

Each firm's manager maximizes:

$$[1 - f(r)]\, \Omega\,(r, \triangle)\,, \tag{8}$$

subject to:[20]

$$\Omega\,(r, \triangle) = \overline{G} + \delta r\,[\mu_J - \mu_H] + \delta r A, \tag{9}$$

$$f(r)\Omega\,(r, \triangle) = [1 + \triangle]\,R. \tag{10}$$

In the program above, $[1 - f]\Omega(r, \triangle)$ is the fraction of firm value captured by the manager ((8)), with $\Omega(r, \triangle)$ being defined in (9), and

$$\overline{G} \equiv \delta\mu_H + [1 - \delta]\mu_L. \tag{11}$$

4.3 General Mechanism in the Second Best Case

We present the general mechanism for the two-type case with $r \in \{r_a, r_b\}$ and $r_a < r_b$. From standard arguments, it follows that the firm with r_a will receive its first-best contract, which is a straight equity contract in which

$$f\,(r_a)\,\Omega\,(r_a, \triangle) = [1 + \triangle]R \tag{12}$$

assuming that investing $\triangle R$ is optimal (in the first-best sense) for the r_a firm.[21] These firms will have an incentive to mimic the firms with $r = r_b$. To eliminate this misrepresentation incentive, a firm that reports $r = r_b$ should be asked to pay investors $\varphi(r)$ for cash flow

[20] To obtain (9), note that

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

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 $\overline{G}$ is defined in (1).

[21] The non-mimicry constraint is easier to satisfy if we assume these firms do not invest $\triangle R$. The analysis of the more general case with a continuum of types allows for low-r firms to not participate in the mechanism and thus not invest $\triangle R$.

realizations that are the most informative that the firm did *not* have a high r.

Initially assume that the r_b firm's participation constraint will be satisfied even with $\Re(r) = 0$. Thus,

$$\mathcal{F}(r) = \{f(r) \mid r \in \{r_a, r_b\}\} \tag{13}$$

is the set of financing terms for firms reporting r. Now, cash flow realizations that are most informative that the firm has a high r are those exceeding x_H, and cash flow realizations that are most informative that the firm has a low r are $x \in [x_L, x_H]$. This is because $x < x_L$ can be realized even with a high r simply because R&D that yielded good initial results turned out to not be very good; this occurs with probability $1 - \delta$. Hence, for incentive compatibility, it is most efficient to ask the firm that reports $r = r_b$ to pay investors $\varphi(r)$ only when $x \in [x_L, x_H]$.

With $f(r_b)$ as the ownership fraction sold by the firm reporting $r = r_b$ to raise $[1 + \omega + \triangle] R$ in financing, if $\varphi(r_b) < [1 - f_{r_b}] x_L$, then the incentive compatibility condition that ensures that the firm with $r = r_a$ will not misrepresent itself as a firm with $r = r_b$ yields:

$$\varphi(r_b) = \frac{[f(r_a) - f(r_b)] \Omega(r_a, \triangle)}{\delta [1 - r_a]} \tag{14}$$

where $f(r_b)$ satisfies

$$f(r_b) \Omega(r_b, \triangle) + \delta [1 - r_b] \varphi(r_b) = [1 + \triangle] R \tag{15}$$

Solving (14) and (15) simultaneously yields

$$\varphi = \frac{[1 + \triangle] R \{\Omega(r_b, \triangle) - \Omega(r_a, \triangle)\}}{\delta \{[1 - r_a] \Omega(r_b, \triangle) - [1 - r_b] \Omega(r_a, \triangle)\}} \tag{16}$$

More Severe Adverse Selection: It is apparent from (16) that $\partial\varphi/\partial\Omega(r_b, \triangle) > 0$, so φ increases as adverse selection worsens. At some point, for $r_b - r_a$ sufficiently high, incentive compatibility will demand $\varphi(r_b) > [1 - f(r_b)] x_H$. This will require the firm that reports

$r = r_b$ to liquidate its illiquid asset to pay $\varphi(r_b)\ \forall x \in [x_L, x_H]$.

If insiders are paying a penalty that exceeds their share of the cash flow in a particular state and this requires insiders to incur a dissipative cost, then it follows (trivially) that reducing this dissipative cost will improve efficiency. This leads to the conclusion that insiders should be given full ownership of the firm's cash flows when $x \in [x_L, x_H]$.

Now, given this ownership structure, if $\Omega(r_b)$ and l^{-1} are large enough, it is possible that the expected utility of insiders in a firm with $r = r_b$ is less than what they could get by avoiding investing $\triangle R$ and just relying on straight equity financing. To ensure that this firm's participation constraint is satisfied with the R&D payoff-enhancement investment, a payment would have to be made in a state that interferes the least with incentive compatibility. This is the state in which $x < x_L$ is the same for all firms, regardless of r. Thus, $\Re(r_b)$ should be paid to the firm's insiders when $x < x_L$.

We show in the next subsection that introducing a financial intermediary can improve welfare, and with an intermediary it is welfare-enhancing to let insiders own all of the firm's cash flows when $x < x_L$. So we will use that specification here as well to characterize the optimal penalty φ.

So now we have a situation in which the firm issues equity claims that: (i) share cash flows between insiders and investors when $x > x_H$; (ii) give insiders all of the cash flows when $x \leq x_H$; and (iii) ask insiders to pay investors φ when $x \in [x_L, x_H]$.

For the analysis that follows, we define:

$$\hat{\Omega}(r, \triangle) \equiv \Omega(r, \triangle) - V_L - V_H(r) \tag{17}$$

where

$$\Omega(r, \triangle) = \delta r \mu_J + \delta[1 - r]\mu_H + [1 - \delta]\mu_L + \delta r A \tag{18}$$

$$V_L \equiv [1 - \delta]\mu_L \tag{19}$$

$$V_H(r) \equiv \delta[1 - r]\mu_H \tag{20}$$

Now, a firm reporting $r = r_b$ will raise the necessary financing, $[1 + \triangle] R$, by selling a fraction $\hat{f}(r_b)$ and promising to pay a penalty $\hat{\varphi}(r_b) \equiv \hat{\varphi}$ if $x \in [x_L, x_H]$, whereas a firm reporting $r = r_a$ must sell a fraction $\hat{f}(r_a)$ to raise the necessary financing, with no penalty. The pricing constraints are now

$$\hat{f}(r_b)\,\hat{\Omega}(r_b, \triangle) + \delta[1 - r_b]\,\hat{\varphi} = [1 + \triangle] R \tag{21}$$

$$\hat{f}(r_a)\,\hat{\Omega}(r_a, \triangle) = [1 + \triangle] R \tag{22}$$

And the IC constraint for the r_a firm to not mimic the r_b firm is:

$$\begin{aligned} \left[1 - \hat{f}(r_b)\right] \hat{\Omega}(r_a, \triangle) + V_H(r_a) + V_L - \delta[1 - r_a]\left\{l^{-1}[\hat{\varphi} - \mu_H] + \mu_H\right\} \leq \\ \left[1 - \hat{f}(r_a)\right] \hat{\Omega}(r_a, \triangle) + V_H(r_a) + V_L \end{aligned} \tag{23}$$

This now leads to:

Lemma 1: *The optimal penalty is:*

$$\hat{\varphi} = \frac{[1 - l]\,\mu_H}{U_1} + \frac{[1 + \triangle]\,R U_2}{U_1} \tag{24}$$

where

$$U_1 \equiv \frac{l^{-1}[1 - r_a] - [1 - r_b]\,\hat{a}_b}{l^{-1}[1 - r_a]} \tag{25}$$

$$U_2 \equiv \frac{[1 - \hat{a}_b]}{\delta[1 - r_a]\,l^{-1}} \tag{26}$$

$$\hat{a}_b \equiv \frac{\hat{\Omega}(r_a, \triangle)}{\hat{\Omega}(r_b, \triangle)} \in (0, 1) \tag{27}$$

Thus, we have characterized a non-linear scheme in which high payoffs ($x > x_H$) are linearly shared via equity, intermediate payoffs ($x \in [x_L, x_H]$) all go to outside investors who also receive an additional penalty $(\varphi - x)$ from insiders in these states, and insiders are "rewarded" by having 100% ownership of the firm when the cash flow is $x < x_L$.

We note that allowing contracts that require insiders to liquidate their illiquid claims to make payouts violates the limited liability that goes with equity. While one may object to permitting a violation of limited liability, these schemes emerge as optimal contracts only if they increase the insider's utility relative to equity. Thus, entrepreneurs are willing to adopt such contracts, similar to owners of small firms being willing to pledge personal assets as collateral for bank loans to their firms. Furthermore, the mechanism design illustrates a possible way to address commonly-encountered frictions in R&D financing, without claiming uniqueness in a general sense. That is, the contracts are uniquely optimal only within the feasible space of contracts we consider. An interesting aspect of these contracts is that they can be implemented with options. Of course, the use of illiquid assets to meet payouts under these contracts made lead to some welfare loss, which opens the door for welfare improvement with a financial intermediary.

4.4 Welfare Enhancement with a Financial Intermediary

We now show that financial intermediary can improve welfare by reducing the dissipative cost associated with a penalty φ. The basic idea is as follows. A financial intermediary can contract with numerous firms. With each firm, the contract would stipulate that the firm transfers all the cash flow it possesses to the intermediary when $x < x_L$, and when $x \in [x_L, x_H]$ the firm would pay a penalty $\overline{\varphi}_I$ to the intermediary that is lower than the penalty $\overline{\varphi}$ paid by the intermediary to investors, with the intermediary being compensated for the difference through its receipt of the firm's cash flows when $x < x_L$. By holding a diversified portfolio of such contracts with numerous firms, the intermediary can make payments on behalf of some firms that need to pay penalties while collecting payments from other firms that experience cash flows falling below x_L. We assume the intermediary operates competitively and earns zero expected profit.

For the intermediary to improve welfare with such a scheme, it must be able to do something that the market cannot do. Following financial intermediation theory which emphasizes that intermediaries create value by developing expertise in screening and monitoring firms (e.g. Ramakrishnan and Thakor (1984)) we assume that after contracting with the firm and receiving the reports of their r values, the intermediary can produce an informative signal s, privately observed by the intermediary and the firm, which tells the intermediary whether the firm reported truthfully, with:

$$\Pr(s = \tilde{r} \mid r = \tilde{r}) = 1, \ \Pr(s = \tilde{r} \mid s \neq \tilde{r}) = m \in (0.5, 1) \tag{28}$$

where $\tilde{r}$ is the r reported by the firm, and r is the true r. This means that a firm that reports truthfully has no risk of being misidentified as not having reported truthfully, but a firm that did not report truthfully has a probability m of being detected as not being truthful. The intermediary can thus contract with the firm to pay $\overline{\varphi}_I < \overline{\varphi}$ if the signal s reveals no misreporting, and to pay $\overline{\varphi}$ if misreporting is detected. Because we also want to prove that allowing the firm's insiders to keep *all* the cash flows $x < x_L$ is optimal, we now assume that they keep only a fraction κ of the cash flows when $x < x_L$, with fraction $[1 - \kappa]$ going to investors. This means that when $x < x_L$ occurs, insiders can transfer only κx to the intermediary. We will show that welfare is strictly increasing in κ.

Thus, a firm that reports r_b keeps 100% of the ownership of the firm for all cash flows $x \in [x_L, x_H]$. In exchange, it pays the intermediary a penalty of $\overline{\varphi}_I$ if no misreporting is detected by the intermediary and transfers all of its cash flow ownership to the intermediary if $x < x_L$, with the intermediary paying investors $\overline{\varphi}$ if $x \in [x_L, x_H]$. A firm that reports r_a need not enter into a contract with the intermediary and keeps 100% of the ownership of cash flows for $x \in [x_L, x_H]$, and a fraction κ of the cash flows when $x < x_L$. The firm reporting r_b sells a fraction $\overline{f}(r_b)$ of its value for $x > x_H$ to investors, and the firm reporting r_a sells a fraction $\overline{f}(r_a)$ of its value to investors for $x > x_H$.

Now the pricing constraints are:

$$\overline{f}(r_b)\,\hat{\Omega}(r_b,\triangle)+\delta[1-r_b]\,\overline{\varphi}+[1-\kappa]V_L=[1+\triangle]\,R \tag{29}$$

$$\overline{f}(r_a)\,\hat{\Omega}(r_a,\triangle)+[1-\kappa]V_L=[1+\triangle]\,R \tag{30}$$

$$\delta[1-r_b]\,\overline{\varphi}=\delta[1-r_b]\,\overline{\varphi}_I+\kappa V_L \tag{31}$$

where (31) is the zero-profit condition for the intermediary.

The IC constraint is:

$$\begin{aligned}[1-f(r_b)]\,\hat{\Omega}(r_a,\triangle)+V_H(r_a)-\delta[1-r_a]\left[l^{-1}\left\{\overline{\varphi}_I+\frac{m\kappa V_L}{\delta[1-r_b]}-\mu_h\right\}+\mu_h\right]&\\ \leq\left[1-\overline{f}(r_a)\right]\hat{\Omega}(r_a,\triangle)+V_H(r_a)+\kappa V_L&\end{aligned} \tag{32}$$

This now leads to the following result:

Proposition 2: *The optimal penalty structure with an intermediary is:*

$$\overline{\varphi}(r_b)=\frac{[1-l]\mu_H}{U_1}+\frac{[1+\triangle]\,RU_2}{U_1}+\frac{\kappa V_L[1+m]}{U_1\delta[1-r_b]}+\frac{\hat{a}_b[1-\kappa]V_L}{U_1\delta[1-r_a]\,l^{-1}} \tag{33}$$

$$\overline{\varphi}_I(r_b)=\overline{\varphi}-\frac{\kappa V_L}{\delta[1-r_b]} \tag{34}$$

The intermediary's participation improves welfare. For m sufficiently high, welfare is strictly increasing in κ.

The intuition behind the welfare improvement with an intermediary is that post-reporting monitoring by the intermediary reduces the attractiveness of mimicking the r_b firm, so incentive compatibility can be achieved at lower cost.[22] The proposition also says that when intermediation is sufficiently valuable, giving insiders 100% ownership of the cash flows when

[22]For simplicity, we assume no moral hazard on the part of the intermediary and no cost of producing the signal. Including these features would require the intermediary to have sufficient equity capital to resolve the moral hazard (e.g. Holmstrom and Tirole (1997)).

$x < x_L$ is optimal. The reason is that the more insiders own in these states, the more they can transfer to the intermediary and hence the greater is the reduction in the dissipative cost of the penalty $\overline{\varphi}_I$ that can be achieved.[23]

It is useful to compare the welfare contribution of the intermediary in this model with previous theories of financial intermediary existence, e.g. Diamond (1984) and Ramakrishnan and Thakor (1984). In both theories, the optimal (equilibrium) size of the intermediary is infinite. In Diamond (1984) this is because the dissipative penalty on the intermediary for cash flows falling below the promised amount to depositors vanishes in the limit due to the intermediary's infinitely many i.i.d. loans/projects. In Ramakrishnan and Thakor (1984), this is because the efficiency of the optimal second-best contract between investors and the intermediary that is screening firms approaches first-best efficiency as the number of screening agents in the intermediary approaches infinity, with free-riding incentives eliminated by internal monitoring. What the intermediary in our model has in common with the intermediaries in these seminal theories is that it reduces distortions caused by informational frictions.

There are, however, three important differences that generate a new potential contribution of financial intermediaries. First, unlike the previous theories, the intermediary in our model increases the cost of mimicry for firms through its monitoring, which reduces the penalty that needs to be imposed on the firm in low-cash-flow states. Second, the key novel role of the intermediary in our model is to enable a "transfer" of the firm's cash flow from the "surplus" cash flow state to the "deficit" cash flow state in which it faces a penalty. This enhances welfare by permitting a further reduction of the dissipatively costly penalty on the firm that is associated with market financing. Central to the intermediary's ability to do this is that it has relationships with multiple firms seeking market financing. Third, while the intermediary improves welfare, it never attains first best. In a nutshell, the contribution of

[23]The reason why intermediation needs to be sufficiently valuable (which is a sufficiency condition) is that giving insiders 100% ownership of the firm when $x < x_L$ widens the relative value gap between the r_b and r_a firms for the portion of firm value they sell to investors, making incentive compatibility more challenging.

the intermediary in our model is to help firms implement more efficient contracts with which to finance themselves in the market, using *interfirm* state-contingent transfers to enhance efficiency, rather than elevating aggregate investment.

5 Implementing the Mechanism with Options: A Mechanism Design Approach

We will show that a general scheme like the one characterized in Section 4 can be implemented with *options* in the case in which r lies in a continuum $[r_a, r_b]$. The analysis shows, given specific tractable distributional assumptions, the possibility of implementing the general mechanisms with a class of financial contracts that are widely traded and understood in practice.

5.1 Preliminaries

As in the previous analysis, we will first analyze the mechanism without an intermediary and assume that insiders own all of the firm when $x < x_L$, whereas investors own all of the firm when $x \in [x_L, x_H]$.[24] So insiders sell to investors a share f of the firm in the $x > x_H$ cash flow states and raise $[1 + \omega + \triangle]R$. In addition to this equity financing, the firm also sells to investors a *put option* with a strike price of $\zeta(r)$ that enables investors to put the firm to insiders for $\zeta(r)$ when $x \in [x_L, x_H]$. This put option has attached to it a digital option that switches on and off based on the realized x. When $x \in [x_L, x_H]$, investors have a put on the firm with a strike price of $\zeta(r)$, and when $x < x_L$, insiders have a put on the firm at the same strike price.

Thus, 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 the insiders long in the put and investors short in

[24]Investors owning 100% of the firm when $x \in [x_L, x_H]$ seems different from the previous set-up. However, we will show that with options, the states in which insiders pay φ to investors, the insiders will effectively own all the firm.

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 if $\zeta > x$, surrender x, and receive ζ. When $x < x_L$, insiders exercise their put option, surrender x, and receive ζ. *Figure 3* depicts the option payoffs from the perspectives of both the manager and investors.

[Insert Figure 3 Here]

When investors exercise their put option, the firm's cash flow is not enough to satisfy their claim. Thus, the manager must liquidate his personal assets Λ at a cost. This requires monitoring by the intermediary and a precommitment to the intermediary's scheme, which may be unavailable with market financing. Absent such monitoring and precommitment, the manager may invoke the firm's limited liability and not sell personal assets at a cost to settle any payment on the put option, unraveling the scheme.

A firm not participating in the scheme must seek market financing, as in the previous section. Thus, the intermediary's mechanism Ψ can be described as:

$$\Psi : [r_a, r_b] \to \mathbb{R}_+ \times [0,1]. \tag{35}$$

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 $P_0(\tilde{r} \mid r)$ be the value of the put option that investors (outsiders) have and $\hat{P}_0(\tilde{r} \mid r)$ be its cost to insiders when the firm reports $\tilde{r}$ and its true parameter value is r, with $P(r \mid r) \equiv P(r)$. The investors then determine the fractional ownership f that the firm must sell in order to raise $[1 + \triangle] R$ at $t = 1$. We rely on our previous result that equity dominates debt in the external financing pecking order.

5.2 Analysis of the Mechanism

We start by noting that the first best (analyzed in Section 4.2) cannot be implemented when r is privately known.

Lemma 2: *The first-best solution is not incentive compatible.*

The reason why the first best is not incentive compatible is that a firm with a higher r is more valuable, so masquerading as a firm with a higher r permits the firm to raise financing by giving up a lower ownership share.

Let $U(\tilde{r} \mid r)$ be the expected payoff of a firm with a true parameter r that reports $\tilde{r}$ under the mechanism. Recalling the $l \in (0,1)$ is the fraction of illiquid assets that can be liquidated, with asymmetric information, the mechanism designer's problem can be expressed as that of designing functions $\pi \in [0,1]$ and ζ to solve:

$$\max \int_{r_a}^{r_b} \pi(r) \left\{ \Omega(r, \triangle) - P_0(r) l^{-1} + P_I(r) - \Omega^* \right\} z(r)\, dr, \tag{36}$$

subject to

$$\Omega(r, \triangle) \equiv \beta(r) \equiv \hat{\Omega}(r, \triangle) + V_L + V_H, \tag{37}$$

$$U(\tilde{r} \mid r) = \pi(\tilde{r}) \left\{ \left[1 - \tilde{f}\right] \hat{\Omega}(r, \triangle) - P_0(\tilde{r} \mid r) l^{-1} + P_I(\tilde{r} \mid r) + V_L \right\}, \tag{38}$$

$$U(r) \geq U(\tilde{r} \mid r) \;\; \forall r, \tilde{r} \in [r_a, r_b], \tag{39}$$

where P_0 is the value to investors of their put option at $t = 1$, $P_0 l^{-1}$ is the expected cost of this option to insiders, and P_I is the value of the insiders' option, with $\tilde{f} \equiv f(\tilde{r})$ being determined by:

$$\tilde{f}\hat{\Omega}(\tilde{r}) + V_H(\tilde{r}) + P_0(\tilde{r}) - P_I(\tilde{r}) = [1 + \triangle] R, \tag{40}$$

and $U(r \mid r) \equiv U(r)$. Here Ω^* is the total value of each firm that raises market financing and does not use the mechanism. Assume for now that Ω^* is mechanism-independent; we will prove this shortly. That is, the mechanism designer maximizes the incremental surplus from mechanism design relative to the market financing outcome.

In (36) the mechanism designer maximizes the expectation (taken with respect to r that the designer does not know) of the total value of the firm Ω minus the deadweight cost of paying out on the put option, $P_0 l^{-1}$, minus the value Ω^* attainable with market financing. (37) is simply the firm value when the firm's true parameter is r. (39) is the global incentive compatibility (IC) constraint, and (40) is the competitive capital market pricing constraint.

Henceforth, for simplicity, we shall assume that L, H, and J are all uniform. The put option values (assuming that $\zeta(r) > x_L$, something we will verify later as being associated with the optimal solution) for a firm with a true r and a reported $\tilde{r}$ are given by:

$$P_0\left(\tilde{r} \mid r\right) = \delta[1-r] \int_{x_L}^{\zeta(\tilde{r})} \left[\zeta\left(\tilde{r}\right) - x\right] \, dH, \tag{41}$$

$$P_I\left(\tilde{r} \mid r\right) = [1-\delta] \int_{0}^{x_L} \left[\zeta\left(\tilde{r}\right) - x\right] \, dL. \tag{42}$$

Simplifying (41) and (42) and defining $\zeta\left(\tilde{r}\right) = \tilde{\zeta}$ gives:

$$P_0\left(\tilde{r} \mid r\right) = \frac{\delta[1-r]\left[\tilde{\zeta} - x_L\right]^2}{2\left[x_H - x_L\right]}, \tag{43}$$

$$P_I\left(\tilde{r} \mid r\right) = [1-\delta]\left[\tilde{\zeta} - \mu_L\right]. \tag{44}$$

For notational convenience, we define

$$C_0(r) \equiv \frac{\delta[1-r]\left[\mu_J - \mu_H\right]}{\Omega(r)}. \tag{45}$$

$$C_1(r) \equiv \frac{[1+\triangle]R - V_H}{\hat{\Omega}(r)}. \tag{46}$$

$$C_2(r) \equiv 1 + \phi(r)\delta\left[\mu_J + A\right]\left[\hat{\Omega}(r)\right]^{-1}. \tag{47}$$

We assume in our final two restrictions that the function $\phi(r) \equiv \frac{1-Z(r)}{z(r)}$ is non-decreasing in r and bounded, and that l is large enough—the personal asset liquidation cost is not too high:

Restriction 3: $\phi(r) \equiv \frac{1-Z(r)}{z(r)}$ is non-decreasing in r and satisfies

$$\inf_r \left\{ \frac{1-r}{\phi(r)} \right\} > \sup_r \left\{ l^{-1} - C_0(r) \right\} \forall r \tag{48}$$

Restriction 4: The personal asset liquidation cost is not too high:

$$\frac{1-r_b}{\phi\left(r_b\right)} > l^{-1} \left[C_2\left(r_b\right)\right]^{-1}. \tag{49}$$

We now present a result that converts the global IC constraint (39) into a local constraint.

Lemma 3: *The global IC constraint (39) is equivalent to:*

1. $U'(r) \equiv N(r) = \pi(r) \left[\delta \left\{ [1-f(r)] \left[\mu_J + A \right] \right\} + \frac{l^{-1}\delta[\zeta - x]^2}{2[x_H - x_L]} \right]$ *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. *(39) holds where* U' *does not exist.*

This lemma permits the infinite number of constraints embedded in (39) to be replaced with conditions involving the first and second derivatives of U. We can now show:

Lemma 4: *The value of the market financing option for any firm,* Ω^**, is independent of the intermediary's mechanism.*

This is in contrast to the Philippon and Skreta (2012) and Tirole (2012) models in which reservation utilities are endogenous—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 so that it is optimally preferred to market financing by the highest quality firms, and it is only the firms at the lower 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 them. Moreover, the mechanism ensures that any firm using the mechanism gets an expected utility 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.

Lemma 5: *The regulator's mechanism design problem in (36)–(40) is equivalent to designing the functions π and ζ to maximize:*

$$\int_{r_a}^{r_b} \pi(r) \left\{ \phi(r)\delta \left[\frac{l^{-1}[\zeta - x_L]^2}{2[x_H - x_L]} + [\mu_J + A] \left[1 - C_1(r) - \frac{P(r)}{\hat{\Omega}(r)} \right] \right] \right\} z(r)\, dr$$
$$+ \int_{r_a}^{r_b} \pi(r) \left\{ [1 + \triangle] R - \Omega^* - P(r) \right\} z(r)\, dr, \tag{50}$$

where

$$P(r) \equiv P_0(r) - P_I(r). \tag{51}$$

The following result characterizes the optimal mechanism.

Proposition 3: *The optimal mechanism involves:*

1. *A put option strike price of*

$$\zeta(r) = x_L + \frac{[x_H - x_L][1 - \delta] C_2(r)}{\delta \left\{ C_2(r)[1 - r] - \phi(r) l^{-1} \right\}}, \tag{52}$$

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

2.

$$\pi(r) = \begin{cases} 1 & \textit{if } r \geq r^* \in [r_a, r_b] \\ 0 & \textit{otherwise} \end{cases}. \tag{53}$$

The intuition is as follows. Firms with lower r values want to masquerade as firms with higher r values. 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) has a higher liability under the put option sold to investors if a higher r is reported. This mechanism is incentive compatible because it is less costly for a firm with a higher true r to be short in such an option.

In addition, the digital option causes the insiders to be long in the put and investors short in 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 r values, the reduction in the expected cost of personal asset liquidation is greater for the firms with higher r values, 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 the insiders. The probability of being allowed to participate in this mechanism is one as long as the mechanism achieves a higher value of the objective function than with direct market financing. Otherwise, the firm is asked to rely exclusively on direct market financing.[25]

This mechanism overcomes two major impediments to financing risky R&D—convincing investors that there is enough upside in the R&D to make it attractive for them to invest, and convincing the entrepreneur (insiders) that there is sufficient downside protection against

[25] The reason why the density function over unknown firm types, z, does not appear in the optimal solution is because this solution involves investors earning zero expected profit *on each* r, in line with the competitive equilibrium concept. See Besanko and Thakor (1987) for another mechanism design model in a competitive market setting for a similar result.

the failure of the R&D that it is worth undertaking it. The mechanism also explains why pledging the illiquid assets (worth Λ to insiders) as collateral for a loan will not address the problem being solved by the optimal mechanism. Collateral would transfer to investors upon default by the firm, so it would help to insure investors against firm failure. Here the illiquid asset serves to insure investors against a sufficiently high *upside* not being achieved, whereas it is the entrepreneur/firm that is being insured against failure.

We now explore some of the comparative statics of the optimal mechanism.

Lemma 6: *ζ is decreasing in l and A.*

The strike price ζ represents both a contingent liability for the firm in case the payoff does not exceed x_H (i.e., it falls in $[x_L, x_H)$) and a form of protection if it is very low ($< x_L$). An increase in l means higher liquidity for the insiders' illiquid assets that would need to be used to pay investors in the event the very high ($> x_H$) cash flow is not realized. This means it is less costly for the firm's insiders to insure investors against this event and thus they need to be compensated less in the very-low-cash-flow state ($< x_L$) to offset their loss in liquidating illiquid assets. Since investing $\triangle R$ requires selling a claim against $\tilde{A}$, investors can be paid less when $x \in [x_L, x_H]$ because a larger A compensates investors more, and its correlation with r means that it partially substitutes for ζ in providing incentive compatibility.

5.3 Interpretation of the Mechanism

Our mechanism can functionally be interpreted as an exchange of put options (insurance contracts) between investors and owner-manager insiders. One contract is offered by insiders to investors, and insures investors against the possibility that the firm misrepresents its chances of the R&D-enhancement succeeding. Since the strike price is increasing in r, this cost makes it progressively more onerous for a firm to misrepresent itself as a high-r firm, thus inducing it to truthfully report its value of r. Put another way, the payoff range of this insurance contract only occurs when x achieves a high cash flow distribution (with cdf H).

Firms with a high likelihood of R&D-enhancement success will not expect to fall into this region (since they will have cash flow x distributed according to cdf J). However, firms with a low likelihood of R&D-enhancement success have a high chance of falling into this region. Of these firms, the ones that truthfully report their (low) value of r will not be invited to participate in the mechanism.[26] The ones that choose to participate by misrepresenting their value of r as being higher will be required to provide an insurance contract to investors.

This insurance contract therefore helps to incentivize investors to provide financing for the R&D-enhancing investment, by protecting them against the risk of financing firms with a relatively low likelihood of achieving very high payoffs. As noted earlier, the combination of this contract with equity can be viewed as putable common stock, which has been used by firms. Thus, the mechanism utilizes an option contract that already exists.

The other contract is offered by investors to insiders, and insures the 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. Such insurance is analogous to "research and development insurance" that is currently offered to firms.

5.4 Implementing the Mechanism: Practical Real-World Issues

The model implies that put options can insure insiders against R&D failures and investors against high R&D payoffs not being realized. An example of R&D failure would be a drug that failed to receive FDA approval, resulting in no sales since the drug does not reach the

[26] It should be noted that the design of the mechanism does not change the behavior of the firms that do not participate in the mechanism and only go to the market to raise financing. In other words, for the firms not investing in the R&D payoff enhancement (and thus not participating in the mechanism), the investment and capital structure analysis of Section 3 of the paper still holds.

market, or unfavorable results in clinical trials resulting in low sales (for example, reduced efficacy amongst a subset of the targeted patient population that significantly reduces the subsequent sales of the company). That is, firms face not only inherent scientific risks in developing new compounds for humans, but also the risk of the FDA regulatory approval process (e.g. DiMasi, Hansen, Grabowski, and Lasagna (1991)). For example, Hanni Pharmaceuticals halted the development of Olita in April 2018, due to the outcomes of clinical trials. Johnson & Johnson's Janssen Biotech halted the clinical development of Atabecestat after Phase 2 clinical trials. Grabowski and Vernon (2000) show that drugs in the bottom two sales deciles account for a negligible proportion of total drug sales. If such failure is encountered, the firm realizes a very low payoff ($< x_L$). The relatively high risk of this occuring is a daunting challenge for many R&D-intensive firms considering the large costs of development.

A very high payoff in the model would correspond to a commercially successful product being developed, such as a blockbuster drug. An example is Minoxidil, originally developed to treat high blood pressure, which became a blockbuster in part because it could be marketed as Rogaine to stimulate hair growth. There are a number of drugs that are similarly pioneers in treating certain conditions and result in very high sales. Crestor, which treats high cholesterol, is another example, with lifetime sales of $56.9 billion.[27] Grabowski and Vernon (2000) document that drugs in the top decile account for more than half of total drug sales.

Between these two extremes are numerous examples of projects that were neither failures nor blockbusters. A number of examples are "orphan drugs" that are developed for rare diseases and hence are expected to be sold in relatively small markets, as well as a broad range of other drugs. For example, Grabowski and Vernon (2000) show that drugs in their sample outside of the first sales decile produced roughly 44% of overall drug sales, compared to 56% for drugs in the top decile. A specific example is a biosimilar launched by Pfizer in late 2016, known as infliximab-dyyb, which by 2019 had acquired only 5% of the US

[27] Other examples include Prilosec for ulcers and Prozac for depression made up a large portion of the top decile of drugs sales from 1988 to 1992 (see Grabowski and Vernon (2000)).

infliximab market.

Our mechanism would require Pfizer (the maker of infliximab-dyyb) to pay investors, whereas investors would pay Hanni Pharmaceuticals due to the failure Olita. Blockbusters like Rogaine (Minoxidil) and Crestor would trigger neither of the two puts.

The interpretation of our mechanism as insurance contracts and guarantees also corresponds to the recently proposed financial innovations in biopharma, while offering insights into how these contracts could be augmented. For example, an "FDA hedge" provides firms insurance against the failure of a drug to get FDA approval; see Philipson (2015) and Jorring et al. (2021) for details.[28] Another innovation is "Phase 2 development insurance", which is offered to biotech firms in exchange for an equity stake in the firm, and pays out when a drug fails Phase 2 R&D trials. These contracts resemble the put sold by investors to insiders. Besides highlighting the value of such contracts, our mechanism indicates that an appropriate *exchange* of insurance contracts between firms and investors in conjunction with equity can attenuate adverse selection, and improve R&D outcomes. As Jorring et al. (2021) point out, these are examples of exchange-traded binary options that are currently traded on several exchanges.

A particular binary option used in practice that is worth discussing here is a Contingent Valuation Right (CVR). These are typically used in M&A deals, and pay investors some pre-specified amount when certain milestones are met. Thus, they are digital option contracts with pre-specified triggers. Event-driven CVRs are common in health care and biotech M&A deals. For example, Sanofi-Aventis' agreement to acquire Genzyme and Celgene's agreement to acquire Abraxis BioScience are examples of CVRs in which future payments were predicated on achieving regulatory milestones and product sales. In both cases, the CVRs provided for additional payments based on FDA approvals being obtained by prespecified dates. A key difference between CVRs and our mechanism is that, with

[28]Jorring et al. (2021) provide a detailed analysis of FDA hedges and also provide "proof of concept". They show, based on granular project level data, that these hedges have a zero-beta property that makes it attractive for investors to offer them as insurance (puts) to drug developers.

CVRs, the acquirer pays the target for achieving good outcomes, i.e., the initial price paid is based on low estimates of future outcomes and then additional payouts are made to the target. In contrast, if we interpret investors in our model as an acquiring firm, then our mechanism awards the target a relatively high price up-front and then demands a payment to the acquirer if very high payoffs are not realized. Another key difference is that our mechanism provides the drug developer insurance against failure.

The interpretation of "investors" in our model is quite broad. They could be deep-pocketed hedge funds or other institutional investors specializing in the biopharma sector and yet are well-diversified relative to drug developers themselves. They could also be resource-rich, publicly-traded large pharma firms that are investing in smaller, publicly-traded yet capital constrained biotech firms. In the latter case, the put option exercised by the inventing biotech firm can be viewed as a pre-negotiated buyout by the acquiring firm (investor) at a predetermined price when the R&D outcome of the biotech firm is poor. Similarly, the put option heldo and exercised by investors could be viewed as the acquiring firm having a pre-negotiated right to acquire the rest of the biotech firm at a predetermined low price when the biotech firm's R&D yields an intermediate payoff, i.e., the payment from the firm to investors when investors exercise their put could be viewed as the difference between the true value of the firm and the lower price at which the acquirer is able to buy it.[29] Such pre-negotiated terms for bilateral M&A transactions are routinely used in the biopharma industry, though they are rarely formulated in option-pricing terminology and analyzed as quantitatively as in our framework, and our analysis also provides a rigorous microfoundation for their deployment.

We may extend this interpretation to think of the financial intermediary as a large pharmaceutical firm (say an Eli Lilly or Pfizer) taking simultaneous positions in numerous small, publicly-traded biotech firms. For example, imagine Eli Lilly taking a position in (publicly-traded) BioNTech and other R&D-intensive biotech firms. As in our intermediation model,

[29]This analogy is not precise, however, unless one associates with this event a dissipative loss suffered by the inventing firm's insiders.

as long as R&D outcomes across these biotech firms are not perfectly correlated, the investing pharma firm can act as a *de facto* intermediary and reduce the liquidation requirement imposed on each inventing firm. Moreover, given the scientific and technical expertise we would expect these investing pharma firms to possess, they could plausibly expected to perform the monitoring and screening provided by the intermediary in our model. This implies that our mechanism creates an opportunity to elevate R&D investment by involving large, established pharma firms with deep resources not only as more efficient providers of capital for R&D-intensive firms than traditional capital market equity investors (e.g. mutual funds and pension funds), but also as entities that perform an intermediary role due to their special industry knowledge and need for diversification and risk transfer.[30]

5.5 Role of Intermediary

Introducing a financial intermediary with r in a continuum has the same effect on mechanism design that it has in the two-type case. it helps to reduce the dissipative cost $P_0 l^{-1}$ by making the global IC constraint easier to satisfy. With an intermediary, the specification would again involve the intermediary being given 100% ownership of all cash flows $x < x_L$ and setting a strike price payment for the insiders (when investors exercise their put) lower if the intermediary's monitoring reveals that insiders reported truthfully. These details are available upon request.

Our mechanism highlights the value of intermediary monitoring and credible precommitment to a coordinating mechanism between firm insiders and investors. The intermediary could be a third-party like an exchange, a financial institution, or consortium of firms.[31] To the extent that existing contracts do not reflect the kind of bilateral R&D insurance that our analysis says is optimal, the implication is that the empirically-documented underinvestment may be attenuated by augmenting the contract space with intermediary assistance.

[30]We thank an anonymous referee for this interpretation.

[31]For example, financial exchanges such as the Chicago Mercantile Exchange, which serve as an intermediary to bring two counterparties together in a financial transaction, can be seen as playing a similar role.

5.6 Empirical Implications

Proposition 3 and Lemma 6 provide empirical implications of the analysis. First, since $\zeta(r)$ is increasing in r, it means that firms with R&D that has higher blockbuster potential will be willing to provide bigger payments to investors for failing to achieve very high payoffs. Second, firms in which insiders have more liquid assets to make payments to investors will also require lower protection from investors against R&D failure. Third, firms that have more non-cash R&D assets whose value is correlated with the R&D generating a blockbuster (i.e. A) will need to offer smaller payments to investors in case blockbuster payoffs are not realized.

6 Conclusion

Using mechanism design theory, we have developed a normative model of financing for R&D-intensive firms. The setting has adverse selection in which firms need to raise capital to invest in R&D with long-term staged investments and low success probabilities—features that typify R&D-intensive firms. We show that market financing leads to underinvestment in R&D.

Our main result involves developing a non-market solution to the underinvestment problem. Using the principles of mechanism design, we show that a mechanism consisting of put options resolves this friction and induces firms to undertake the additional R&D investment. An additional advantage of the mechanism that emerges from this analysis is that it provides the firm with financial resources in the state in which the R&D fails, thereby giving it the resources to be failure tolerant, something the previous research on motivating employees to be innovative has shown is optimal (e.g. Manso (2011)). The involvement of a financial intermediary improves welfare. Central to its ability to do this is its relationships with multiple firms. The analysis thus highlights a novel benefit of an intermediation-assisted coordinating mechanism to enable precommitment in R&D financing.

The mechanism developed here 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)), using private-sector means to facilitate socially valuable R&D.

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$t = 1$	$t = 2$
• Manager has a potentially worthwhile R&D project available. Manager privately knows the firm's r; no one else does. • A firm needs R for initial R&D investment at $t = 1$. • Manager decides whether to invest R or $R + \triangle R$ in an R&D project. • Firm raises financing from equity in the case of market financing, and may use an intermediary with mechanism design (in which case it reports its private information). • The firm's manager could also liquidate personal assets Λ at a cost as an alternative to part of the capital market financing.	• Final R&D payoff x is observed. • If firm invested R at $t = 1$, then $x \sim H$ with probability δ and $x \sim L$ with probability $1 - \delta$. Conditional on $x \sim H$, the value of R&D-dependent assets-in-place is A with probability r and 0 with probability $1 - r$. • If firm also invested additional $\triangle R$ at $t = 1$, then high cash-flow realization (which happens with probability δ) becomes $x \sim J$ with probability r, or remains $x \sim H$ with probability $1 - r$. Conditional on $x \sim J$, the value of non-cash R&D assets is A. • Investors are paid off.

Figure 1: Time-line of Events and Decisions

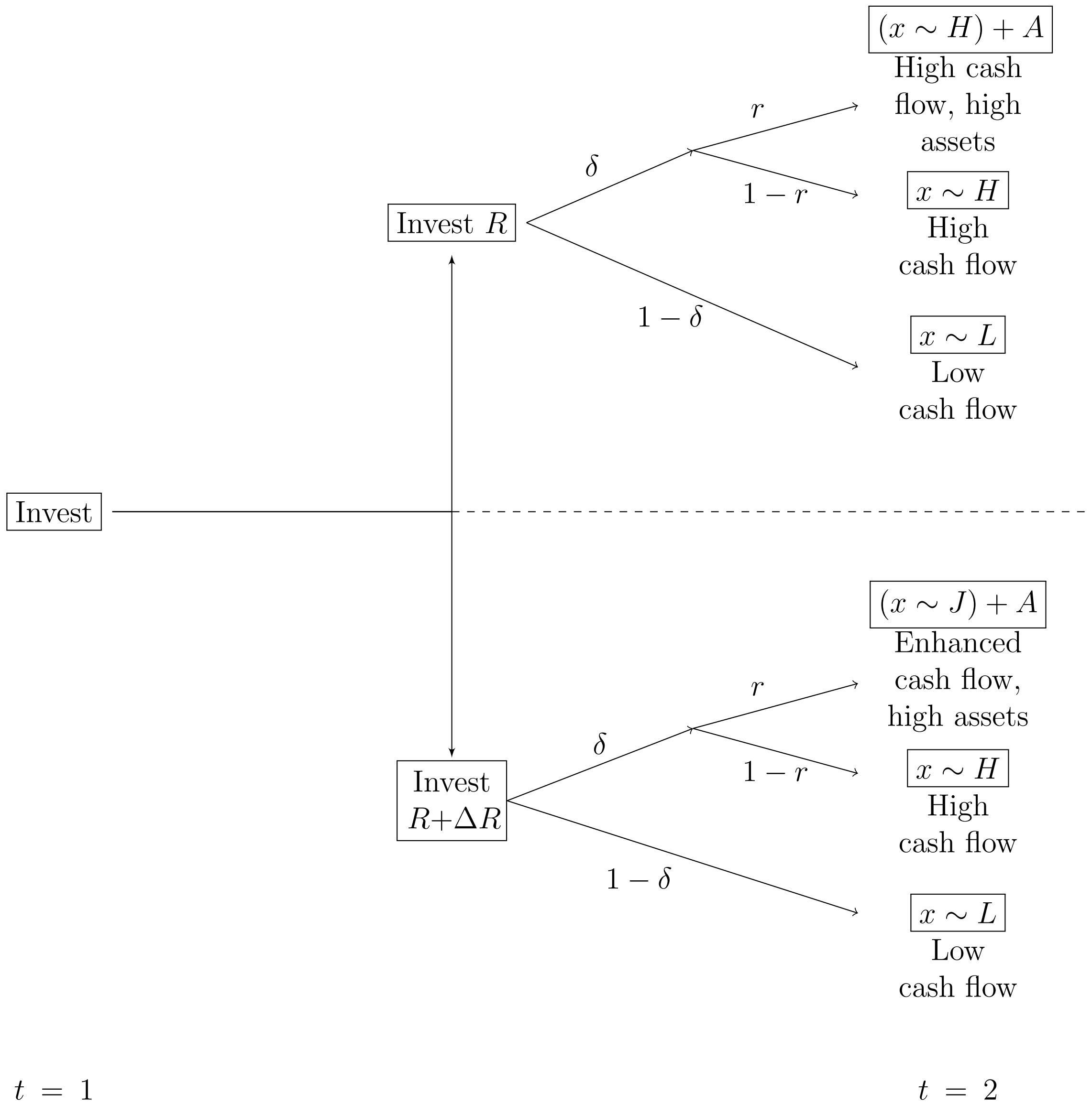

Figure 2: Summary of R&D Investment Timing

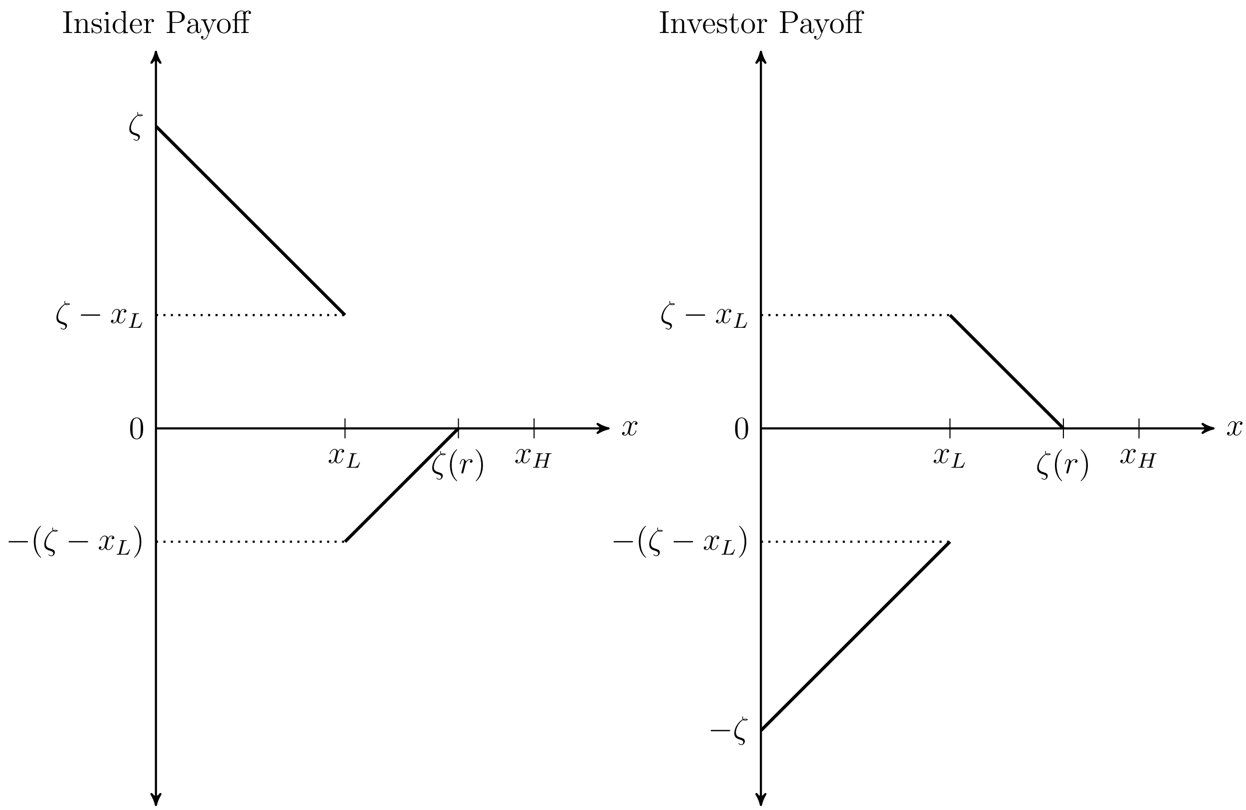

Figure 3: Mechanism Payoffs

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

Appendix: Proofs

Proof of Lemma 1: Clear from the text. ■

Proof of Proposition 1: We will prove that the equilibrium involves pooling by all firms that raise R against the cash flow X, giving investors no claim to the assets in place worth $\tilde{A}$. There are two major steps. First, we will show that it will not work for firms to signal with inside equity ownerships to distinguish themselves and raise $R + \triangle R$. Second, we will show that there is a pooling BPNE in which all firms raise only R, and this equilibrium survives the D1 refinement.

Signaling with Inside Ownership: The idea here is for each firm to liquidate a fraction $\theta \in [0, 1]$ of the insiders' assets to reduce the amount of external financing. This means $\theta(r)l\Lambda$ is provided as internal equity (inside ownership) via this asset liquidation, with $\theta(r)$ varying with r. The breakeven pricing constraint for a type-r firm is

$$f(r) \left[\overline{G} + \delta r A + \delta r \left[\mu_J - \mu_H\right]\right] = R + \triangle R - \theta(r) l \Lambda. \tag{A.1}$$

Now consider the highest value of r, which is r_b, and examine the incentive compatibility condition for some type $r < r_b$ to not mimic r_b. This condition is:

$$\left[1 - f\left(r_b\right)\right] \Omega(r, \triangle) + \Lambda \left[1 - \theta\left(r_b\right)\right] \leq \left[1 - f\left(r\right)\right] \Omega(r, \triangle) + \Lambda \left[1 - \theta\left(r\right)\right], \tag{A.2}$$

where

$$\Omega(r, \triangle) \equiv \overline{G} + \delta r A + \delta r \left[\mu_J - \mu_H\right]. \tag{A.3}$$

Now, the propensity to misrepresent, call it $PM(r)$, is the difference between the left-hand side (LHS) of (A.2) and the right-hand side of (A.2), i.e.,

$$PM(r) = \left[f(r) - f\left(r_b\right)\right] \Omega(r, \triangle) - \Lambda \left[\theta\left(r_b\right) - \theta(r)\right], \tag{A.4}$$

where using (A.1) we have

$$f(r) = \frac{R + \triangle R - \theta(r) l \Lambda}{\Omega(r, \triangle)}. \tag{A.5}$$

Now,

$$\frac{\partial PM(r)}{\partial r} = [f(r) - f(r_b)]\,\Omega'(r,\triangle) + f'(r)\Omega(r,\triangle) - \Lambda\theta'(r). \tag{A.6}$$

Using (A.5), we have

$$f'(r) = \frac{\Omega(r,\triangle)\{-\theta'(r)l\Lambda\} - [R + \triangle R - \theta(r)l\Lambda]\,\Omega'(r,\triangle)}{[\Omega(r,\triangle)]^2}, \tag{A.7}$$

so,

$$f'(r)\Omega(r,\triangle) = -\theta'(r)l\Lambda - \frac{[R + \triangle R - \theta(r)l\Lambda]\,\Omega'(r,\triangle)}{\Omega(r,\triangle)}. \tag{A.8}$$

Substituting (A.8) in (A.6) and simplifying, we get

$$\frac{\partial PM(r)}{\partial r} = -\Omega'(r,\triangle)f(r_b) - \theta'(r)\Lambda[1+l] < 0 \tag{A.9}$$

since $\theta'(r) > 0$ in equilibrium and $\Omega'(r,\triangle) > 0$. This means misrepresentation incentives get weaker as r increases. Moreover, we also know that the lowest type, $r = r_a$, will not signal in equilibrium, i.e. $\theta(r_a) = 0$. Thus, every type $r > r_a$ can basically use the IC constraint that r_a will not mimic it in order to set its $\theta(r)$. This will take care of the global IC constraints. This gives us

$$\theta(r) = \frac{[f(r_a) - f(r)]\,\Omega(r,\triangle)}{\Lambda}, \tag{A.10}$$

where

$$f(r_a) = \frac{R + \triangle R}{\Omega(r_a,\triangle)}. \tag{A.11}$$

Substituting for $f(r_a)$ and $f(r)$ in (A.10) and solving for $\theta(r)$ gives:

$$\theta(r) = \frac{[R + \triangle R]\,[\Omega(r,\triangle) - \Omega(r_a,\triangle)]\,[1-l]^{-1}}{\Omega(r_a,\triangle)}. \tag{A.12}$$

Now if $R + \triangle R$ and $\Omega(r,\triangle)$ are sufficiently large, then $\theta(r) > 1$, making signaling infeasible.

Pooling Equilibrium: If the firm raises R, then it issues equity claims only against x and not its assets in place, $\tilde{A}$. It needs to sell a fraction f of ownership, where

$$
\begin{aligned}
f &= \frac{R}{\overline{\overline{G}}} \\
1 - f &= \frac{\overline{G} - R}{\overline{G}}
\end{aligned}
\tag{A.13}
$$

Thus, the insiders' value will be

$$
\frac{\overline{G} - R}{\overline{G}} + \delta r A. \tag{A.14}
$$

If the firm deviates and raises $R + \triangle R$, it will be viewed as a type r_a firm and will need to sell f_a ownership, where

$$
f_a = \frac{R + \triangle R}{\Omega\left(r_a, \triangle\right)}, \tag{A.15}
$$

where

$$
\Omega\left(r_a, \triangle\right) = \overline{G} + \delta r_a A + \delta r_a \left[\mu_J - \mu_H\right]. \tag{A.16}
$$

Thus, insiders will enjoy a value of

$$
\left[1 - f_a\right] \Omega\left(r, \triangle\right) = \frac{\left\{\overline{G} + \delta r_a A + \delta r_a \left[\mu_J - \mu_H\right] - \left[R + \triangle R\right]\right\} \Omega\left(r, \triangle\right)}{\Omega\left(r_a, \triangle\right)}. \tag{A.17}
$$

We want to show that the expression in (A.14) exceeds that in (A.17) for $r_a > 0$ small enough. This requires

$$
\overline{G}\left\{\overline{G} + \delta r_a A + \delta r_a \left[\mu_J - \mu_H\right] - \left[R + \triangle R\right]\right\} \Omega\left(r, \triangle\right) < \left\{\overline{G} + \delta r_a A + \delta r_a \left[\mu_J - \mu_H\right]\right\}\left\{\overline{G} - R + \delta r A \overline{G}\right\} \tag{A.18}
$$

Now at $r_a = 0$, (A.18) becomes (upon simplification)

$$
\overline{G}\left\{\overline{G} + \delta r \left[\mu_J - \mu_H\right] - 1\right\} < \left[R + \triangle R\right]\left\{\overline{G} + \delta r A + \delta r \left[\mu_J - \mu_H\right]\right\} + R, \tag{A.19}
$$

which clearly holds since $\overline{G} < R + \triangle R$. Thus, by continuity, (A.18) holds for $r_a > 0$ small enough. This means that no type r will wish to defect from the pooling equilibrium in which all firms raise R by issuing claims only against x. Thus, the equilibrium is a BPNE.

Next we prove that the stipulated out-of-equilibrium belief survives the D1 criterion. Consider the pooling equilibrium in which all firms raise R in equity at $t = 1$ and forgo investing $\triangle R$. Suppose a firm defects from this equilibrium by raising $\triangle R$, which would require it to give outside investors a claim to x as well as its assets in place. Let $\tilde{r}$ be the belief assigned by investors to the defector's type. Then the gain from defecting, call it $DG(\tilde{r} \mid r)$,is the difference between the defection payoff and the firm's equilibrium payoff, i.e.,

$$
\begin{aligned}
DG(\tilde{r} \mid r) &= \left[1 - \tilde{f}(\tilde{r})\right] \left\{\overline{G} + q\delta r \left[A + \mu_J - \mu_H\right]\right\} - \left[1 - f(\overline{r})\right] \overline{G} - q\delta r A \\
&= \left[f(\overline{r}) - \tilde{f}(\tilde{r})\right] \overline{G} + \left[1 - \tilde{f}(\tilde{r})\right] \left[q\delta r \left\{A + \mu_J - \mu_H\right\}\right] - q\delta r A
\end{aligned} \tag{A.20}
$$

where

$$
\tilde{f}(\tilde{r}) \Omega(\tilde{r}, \triangle) = [1 + \triangle] R \tag{A.21}
$$

When $DG(\tilde{r} \mid r) = 0$, the firm is indifferent between defecting and not defecting. Let $\tilde{r}^*(r)$ represent this "indifference belief". Since $\partial \tilde{f}(\tilde{r}) / \partial \tilde{r} < 0$, it follows that the firm will prefer to defect whenever $\tilde{r} > \tilde{r}^*(r)$. Thus, using $DG(\tilde{r}^*(r) \mid r) = 0$, we can use (A.20) to obtain:

$$
\tilde{f}(\tilde{r}^*(r)) = \frac{f(\overline{r}) \overline{G} + q\delta r \left[\mu_J - \mu_H\right]}{\overline{G} + q\delta r \left[A + \mu_J - \mu_H\right]}. \tag{A.22}
$$

Thus,

$$
\frac{\partial \tilde{f}(\tilde{r}^*(r))}{\partial r} = \frac{\overline{G} q\delta \left\{\mu_J - \mu_H - \left[R/\overline{G}\right] \left[A + \mu_J - \mu_H\right]\right\}}{\left\{\overline{G} + q\delta r \left[A + \mu_J - \mu_H\right]\right\}^2} < 0, \tag{A.23}
$$

given (4). This means that $\partial \tilde{r}^*(r)/\partial r > 0$. Let $\mathcal{S}(r \mid \triangle R)$ be the set of mixed best responses of investors (in terms of beliefs about the defector's type) having observed the defection $\triangle R$ such that a firm of type r strictly prefers to defect and let $\mathcal{S}^0(r \mid \triangle R)$ be the set of mixed best responses that make the firm indifferent between defecting and not defecting. From the above it is straightforward that whenever $r_1 > r_2$, we have

$$
\mathcal{S}(r_1 \mid \triangle R) \cup \mathcal{S}^0(r_1 \mid \triangle R) \subset \mathcal{S}(r_2 \mid \triangle R). \tag{A.24}
$$

Thus, the posterior belief of investors must assign probability 1 that the defector is r_2. Applying this logic to all $r \in [r_a, r_b]$, we see that any sequential equilibrium that survives as a D1 equilibrium will assign a posterior probability of 1 that the defector is type r_a.

Finally, we formally verify that no firm will deviate from the equilibrium by issuing a claim against $x + \tilde{A}$ in raising R. If a firm with parameter value r does this and is viewed as a type r_a firm, then it must sell a fraction $\hat{f}$ to raise R, where

$$\hat{f}\left[\overline{G} + \delta r_a A\right] = R, \tag{A.25}$$

so the firm's insiders' payoff is

$$\begin{aligned}\left[1 - \hat{f}\right]\left[\overline{G} + \delta r_a A\right] &= \left[1 - \frac{R}{\overline{G} + \delta r_a A}\right]\left[\overline{G} + \delta r A\right] \\ &= \frac{\left[\overline{G} + \delta r_a A - R\right]\left[\overline{G} + \delta r A\right]}{\overline{G} + \delta r_a A}.\end{aligned} \tag{A.26}$$

If insiders use their equilibrium strategy, their payoff is

$$\left[\frac{\overline{G} - R}{\overline{G}}\right]\overline{G} + \delta r A. \tag{A.27}$$

The gain from defection is the difference between (A.26) and (A.27), i.e.,

$$\hat{D}G(r) = R\overline{G}\left\{\frac{1}{\overline{G}} - \frac{1}{\overline{G} + \delta r_a A}\right\} - \delta r A\left\{\frac{R}{\overline{G} + \delta r_a A}\right\}. \tag{A.28}$$

Clearly, $\partial \hat{D}G(r)/\partial r < 0$, which means firms with lower values of r gain more from the defection. Using previous arguments from this proof, it follows that the D1 criterion will assign a probability of 1 that the deviant firm has $r = r_a$. ■

Proof of Lemma 1: From the IC constraint (23), we obtain

$$\hat{\varphi} = \frac{\left[\hat{f}(r_a) - \hat{f}(r_b)\right]\hat{\Omega}(r_a, \triangle) + \delta q\left[1 - r_a\right]\mu_H\left[l^{-1} - 1\right]}{q\delta\left[1 - r_a\right]l^{-1}}. \tag{A.29}$$

Substituting for $\hat{f}(r_b)$ from the pricing constraint (21) into (A.29) and rearranging, we get (24). ■

Proof of Proposition 3: Since the IC constraint (32) is binding in equilibrium, using (32) as an equality and using (29)-(31) leads to (33). Note that (34) is a direct consequence of (31).

Since investors and the insiders in the r_a firm get the same payoffs in all schemes, welfare can be assessed by examining the utility of the insiders in the r_b firm. This utility is:

$$U_b = \left[1 - \overline{f}\left(r_b\right)\right] \hat{\Omega}\left(r_b, \triangle\right) + V_H - \delta\left[1 - r_b\right]\left\{l^{-1}\left[\overline{\varphi}_I - \mu_H\right] + \mu_H\right\} \tag{A.30}$$

Substituting for $\overline{f}\left(r_b\right)$ from (29) and simplifying, we can write (A.30) as:

$$U_b = \hat{\Omega}\left(r_b, \triangle\right) - [1 + \omega + \triangle]R + V_L + \kappa V_L\left[l^{-1} - 1\right] - \delta\left[1 - r_b\right]\overline{\varphi}\left[l^{-1} - 1\right] \tag{A.31}$$

Now, from (33) we see that:

$$\frac{\partial \overline{\varphi}\left(r_b\right)}{\partial m} = \frac{-\kappa V_L}{U_1 \delta\left[1 - r_b\right]} < 0. \tag{A.32}$$

Furthermore,

$$\frac{\partial U_b}{\partial m} = -\delta\left[1 - r_b\right]\left[l^{-1} - 1\right]\left[\partial \overline{\varphi} / \partial m\right] > 0. \tag{A.33}$$

Thus, intermediation improves welfare.

Next, after some simplification:

$$\frac{\partial U_b}{\partial k} = V_L\left\{\left[l^{-1} - 1\right] + \frac{\hat{a}_b}{U_1 \delta\left[1 - r_a\right] l^{-1}} - \frac{\left[l^{-1} - 1\right][1 - m]}{U_1}\right\} > 0 \tag{A.34}$$

for m large enough. ■

Proof of Lemma 2: Consider $r_1 < r_2$ and suppose the intermediary asks each firm to report its r and then implement the first-best solution. Let f_i be and ownership fraction sold by the firm corresponding to a report of r_i. Then if the r_1 firm reports r_2, its insiders' expected utility is

$$\left[1 - f_2\right] \Omega\left(r_1\right) \quad > \quad \left[1 - f_1\right] \Omega\left(r_1\right), \tag{A.35}$$

which follows since $f_1 > f_2$. Note that $f_1 > f_2$ follows from (40) and the fact that $\Omega(r, \triangle)$ defined in (37) is strictly increasing in r and the right-hand side of (A.35) is a constant. Thus, the r_1 firm will misreport its type as r_2. ■

Proof of Lemma 3: Substituting from (40) into (38), we can write:

$$\begin{aligned} U(r) &= \left[\Omega(r,\triangle) - [1+\triangle] + P_0 - P_0 l^{-1}\right]\pi(r) \\ &= \pi(r)\left[\Omega(r,\triangle) - [1+\triangle]R - \left[l^{-1}-1\right]P_0(r)\right]. \end{aligned} \tag{A.36}$$

We will first show that (39) implies parts 1 and 2 of the lemma. Note that we will henceforth write $P_I(\tilde{r} \mid r) \equiv P_I(\tilde{r})$ since its value is dependent only on the reported r. From (39) we have that $U(r \mid r) \geq U(\tilde{r} \mid r)$, so:

$$\begin{aligned} & \pi(r)\left[\Omega(r,\triangle) - [1+\triangle]R - \left[l^{-1}-1\right]P_0(r)\right] \\ \geq\ & \pi(\tilde{r})\left[\left[1-\tilde{f}\right]\Omega(r,\triangle) - P_0(\tilde{r} \mid r)l^{-1} + P_I(\tilde{r}) + V_L\right]. \end{aligned} \tag{A.37}$$

From ((43)) we have

$$P_0(\tilde{r} \mid r) = P_0(\tilde{r}) + \frac{\delta\left[\tilde{r}-r\right]\left[\tilde{\zeta}-x_L\right]^2}{2\left[x_H - x_L\right]}. \tag{A.38}$$

Substituting (A.38) in (A.37) yields:

$$\begin{aligned} & \pi(r)\left[\Omega(r,\triangle) - [1+\triangle]R - \left[l^{-1}-1\right]P_0(r)\right] \\ \geq & \pi(\tilde{r})\left[\left[1-\tilde{f}\right]\hat{\Omega}(\tilde{r},\triangle) - P_0(\tilde{r})l^{-1} - \frac{\delta l^{-1}\left[\tilde{r}-r\right]\left[\tilde{\zeta}-x_L\right]^2}{2\left[x_H-x_L\right]} + P_I(\tilde{r}) + V_L + \left[1-\tilde{f}\right]\hat{\Omega}(r,\triangle) - \left[1-\tilde{f}\right]\hat{\Omega}(\tilde{r},\triangle)\right] \\ = & U(\tilde{r}) + \pi(\tilde{r})\left\{\frac{\delta l^{-1}\left[r-\tilde{r}\right]\left[\tilde{\zeta}-x_L\right]^2}{2\left[x_H-x_L\right]} + \left[1-\tilde{f}\right]\left[\hat{\Omega}(r,\triangle) - \hat{\Omega}(\tilde{r},\triangle)\right]\right\}. \end{aligned} \tag{A.39}$$

Now using (37) we see that

$$\hat{\Omega}(r,\triangle) - \hat{\Omega}(\tilde{r},\triangle) = \delta\left[\mu_J + A\right]\left[r-\tilde{r}\right]. \tag{A.40}$$

Define

$$N(\tilde{r}) \equiv \pi(\tilde{r}) \left\{ \frac{\delta l^{-1} \left[\tilde{\zeta} - x_L\right]^2}{2\left[x_H - x_L\right]} + \left[1 - \tilde{f}\right] \delta \left[\mu_J + A\right] \right\}. \tag{A.41}$$

Substituting (A.41) in (A.39) gives us:

$$U(r) - U(\tilde{r}) \geq [r - \tilde{r}]\, N(\tilde{r}), \tag{A.42}$$

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

$$U(\tilde{r}) - U(r) \geq [\tilde{r} - r]\, N(r), \tag{A.43}$$

which implies

$$U(r) - U(\tilde{r}) \leq [r - \tilde{r}]\, N(r). \tag{A.44}$$

Combining (A.42) and (A.44) yields:

$$[r - \tilde{r}]\, N(\tilde{r}) \leq U(r) - U(\tilde{r}) \leq [r - \tilde{r}]\, N(r). \tag{A.45}$$

Inspection of (A.45) shows that if $r > \tilde{r}$, then the function $N(r)$ is non-decreasing. Given this monotonicity, we can divide through by $r - \tilde{r}$ and take the limit as $\tilde{r} \to r$ to write:

$$\lim_{\tilde{r} \to r} \frac{U(r) - U(\tilde{r})}{\tilde{r} - r} = U'(r) = N(r) > 0 \text{ almost everywhere.} \tag{A.46}$$

Since $N(r)$ is non-decreasing, it follows that $U'' \geq 0$ almost everywhere. Thus we have shown that (39) implies parts 1 and 2 of the Lemma.

Next, we will show that parts 1 and 2 of the lemma imply (39). Note that

$$\begin{aligned} U(r \mid r) - U(\tilde{r} \mid r) &= U(r \mid r) - U(\tilde{r} \mid r) + [r - \tilde{r}]\, N(\tilde{r}) \\ &= \int_{\tilde{r}}^{r} U'(t \mid t) dt - [r - \tilde{r}]\, U'(r \mid \tilde{r}) \\ &\geq 0, \end{aligned} \tag{A.47}$$

using part 1 of the lemma, $U'' \geq 0$, and the mean value theorem for integrals. $\blacksquare$

Proof of Lemma 4: Consider a subset of firms $\mathbb{S} \subset [r_a, r_b]$ that do not participate in the mechanism and thus avail of market financing. Since $U'(r) > 0$ in equilibrium (Lemma 3), it must be true that every $r \in \mathbb{S}$ is smaller than every r that participates in the mechanism. Let $\overline{\overline{r}} = \mathbb{E}[r \mid r \in \mathbb{S}]$ be the expected value of the r of firms that go to market financing. Since $\overline{\overline{r}} < \overline{r}$ (the mean of r over the entire support of $Z(r)$), our earlier analysis implies that none of the firms seeking market financing will raise $\triangle R$ for R&D payoff enhancement. Thus, there will be a pooling equilibrium and each firm's value will be Ω^*, independent of r or the allocations under the mechanism. $\blacksquare$

Proof of Lemma 5: Since the global I.C. constraint has been shown to be equivalent to $U'(r) = N(r)$ almost everywhere in Lemma 3, let us integrate that condition to obtain:

$$\int_{r_a}^{r} U'(\tilde{r} \mid \tilde{r})\, d\tilde{r} = \int_{r_a}^{r} N(\tilde{r})\, d\tilde{r}, \tag{A.48}$$

which means

$$\begin{aligned} U(r) - U(r_a) &= \int_{r_a}^{r} N(\tilde{r})\, d\tilde{r} \\ \Longrightarrow U(r) &= U(r_a) + \int_{r_a}^{r} N(\tilde{r})\, d\tilde{r}. \end{aligned} \tag{A.49}$$

Taking the expectation of (A.49) yields:

$$\begin{aligned} \int_{r_a}^{r_b} U(r) z(r) dr &= U(r_a) + \int_{r_a}^{r_b} \left[\int_{r_a}^{r} N(t) dt \right] z(r) dr \\ &= U(r_a) + \int_{r_a}^{r_b} N(t) \left[\int_{t}^{r_b} z(r) dr \right] dt \\ &= U(r_a) + \int_{r_a}^{r_b} \phi(r) N(r) z(r) dr, \end{aligned} \tag{A.50}$$

where $\phi(r) \equiv \frac{[1-Z(r)]}{z(r)}$. Now we know from (38) that

$$\pi(r) \left[\hat{\Omega}(r, \triangle) + P_I(r) + V_L - P_0(r) l^{-1} \right] = U(r) + \pi(r) f \hat{\Omega}(r, \triangle). \tag{A.51}$$

Substituting in (A.51) for $f\Omega$ from (40) gives us:

$$\pi(r)\left[\hat{\Omega}(r)+P_I(r)+V_L-P_0(r)l^{-1}\right]=U(r)+\pi(r)\left\{[1+\triangle]\,R-P_0(r)-V_H(r)+P_I(r)\right\}. \quad \text{(A.52)}$$

Substituting (A.52) into (36) yields the objective function:

$$\int_{r_a}^{r_b}\left\{U(r)+\pi(r)\left[[1+\triangle]\,R-\Omega^*-P_0(r)+P_I(r)+V_L\right]\right\}z(r)dr. \quad \text{(A.53)}$$

The mechanism designer can give insiders of the lowest type ($r=r_a$) their expected utility with market financing. Let this expected utility be $\overline{u}_a$. Then set $U(r_a)=\overline{u}_a$ and substitute (A.50) in (A.53) above to get

$$\overline{u}_a+\int_{r_a}^{r_b}\left\{\phi(r)N(r)+\pi(r)\left[[1+\triangle]\,R-\Omega^*-P_0(r)+P_I(r)+V_L\right]\right\}z(r)dr. \quad \text{(A.54)}$$

Now use (A.41) and write

$$N(r)=\pi(r)\left\{\frac{q\delta l^{-1}\left[\zeta-x_L\right]^2}{2\left[x_H-x_L\right]}+[1-f]\,q\delta\left[\mu_J+A\right]\right\}, \quad \text{(A.55)}$$

so that, using (40) and (46), the intermediary's objective function (A.54) can be written as:

$$\begin{aligned}&\overline{u}_a+\int_{r_a}^{r_b}\pi(r)\phi\delta\left\{\frac{l^{-1}\left[\zeta-x_L\right]^2}{2\left[x_H-x_L\right]}+\left[\mu_J+A\right]\left[1-C_1(r)+\frac{P(r)}{\Omega(r)}\right]\right\}z(r)\,dr\\&+\int_{r_a}^{r_b}\pi(r)\left\{[1+\triangle]\,R-P(r)+V_L-\Omega^*\right\}z(r)\,dr. \quad \text{(A.56)}\end{aligned}$$

where $P(r)$ is defined in (51). This completes the proof since maximizing (A.56) is equivalent to maximizing ((50)) because $\overline{u}_a$ is a constant (i.e. independent of the mechanism design functions). ■

Proof of Proposition 3: We now proceed with proving the proposition. From optimal control theory, we know that the value function ζ that maximizes (A.56) is the one that involves maximizing the integral pointwise. Thus, the first-order condition for ζ is:

$$
\begin{aligned}
&l^{-1}\phi(r)\delta\left[\zeta - x_L\right]\left[x_H - x_L\right]^{-1} \\
&-C_2(r)\left\{\delta[1-r]\left[\zeta - x_L\right]\left[x_H - x_L\right]^{-1} - [1-\delta]\right\} = 0.
\end{aligned} \tag{A.57}
$$

The second-order condition is:

$$
l^{-1}\phi(r)\delta\left[x_H - x_L\right]^{-1} - C_2(r)\delta[1-r]\left[x_H - x_L\right]^{-1} < 0, \tag{A.58}
$$

which holds given (49).

Moreover, rewriting $\zeta(r)$ we have:

$$
\zeta(r) = x_L + \frac{\left[x_H - x_L\right]\{[1-\delta]\}}{\delta\left\{[1-r] - \left[\phi(r)/C_2(r)\right]l^{-1}\right\}}, \tag{A.59}
$$

which is (52). Since $\partial C_2(r)/\partial r < 0$ and $\partial \phi(r)/\partial r \geq 0$, it follows that $\partial \zeta(r)/\partial r > 0$. Inspection of (A.56) also reveals that the mechanism designer will set $\pi = 1$ whenever the term multiplying $\pi(r)$ in (A.56) 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. ■

Proof of Lemma 6: Using the expression for $\zeta(r)$ in (52) and express it as

$$
\zeta(r) = x_L + \frac{\left[x_H - x_L\right][1-\delta]}{\delta\left\{C_2[1-r] - \phi l^{-1}\right\}} C_2(r). \tag{A.60}
$$

It is clear from inspecting (A.60) that A appears only in $C_2(r)$. Now,

$$
\begin{aligned}
\frac{\partial C_2(r)}{\partial A} &= \frac{\phi(r)\delta\left\{\hat{\Omega}(r) - \delta r\left[\mu_J + A\right]\right\}}{\left(\hat{\Omega}(r)\right)^2}. \\
&> 0
\end{aligned} \tag{A.61}
$$

Since $\partial \zeta(r)/\partial C_2 < 0$, it follows that $\partial \zeta(r)/\partial A < 0$. ■