Optimal Financing for R&D-Intensive Firms*

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Abstract

We develop a theory of optimal financing for R&D-intensive firms. With only market financing, the firm relies exclusively on equity financing and carries excess cash, but underinvests in R&D. We use mechanism design to examine how intermediated financing can attentuate this underinvestment. The mechanism combines equity with put options such that investors insure firms against R&D failure and firms insure investors against high R&D payoffs not being realized.

Keywords: R&D Investments; Innovation; Capital Structure; Cash Holdings; Mechanism Design

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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 hoary 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 addressing this question theoretically in this paper, we recognize that there are numerous features of R&D investments that may contribute to this funding gap. 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 the frictions discussed above. We lay the groundwork for our analysis by first establishing that,

[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) and Grabowski, Vernon, and DiMasi (2002) and Kerr and Nanda (2015).

under conditions typical for R&D-intensive firms, firms optimally rely exclusively on outside equity and excess cash, rather than debt, to finance R&D. However, this leads to an outcome in which all firms underinvest in incremental payoff-enhancing R&D investments.[4]

The analysis of our base model is consistent with three important stylized facts about R&D-intensive firms: (i) reliance on external financing via stock issues (e.g. Lerner, Shane, and Tsai (2003) and Brown, Fazzari, and Petersen (2009)), and very low leverage (e.g. Bradley, Jarrell, and Kim (1984), Himmelberg and Petersen (1994), and Thakor and Lo (2017));[5] (ii) large cash balances (e.g. Brown and Petersen (2011) and Begenau and Palazzo (2016));[6] and (iii) underinvestment in R&D even by publicly-traded firms (e.g. Brown and Petersen (2011) and Hall and Lerner (2010)).

The underinvestment with market financing leads us to our main analysis, which is normative. We explore whether the market financing outcome can be improved upon with an intermediary that extracts a *binding precommitment* from the firm's insiders to make costly ex post payouts from personal wealth. The intermediary designs a mechanism to elicit truthful reports from firms about their privately-known profitability of an additional R&D investment.[7] 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,

[4]We also provide an extension of our base model in which firms use a limited amount of debt, but the underinvestment persists.

[5]Our explanation for low leverage relies on risk shifting and the presence of R&D tax shields that reduce the value of debt tax shields, which is different from the argument that R&D firms avoid debt due to the lack of tangible assets (Hart and Moore (1994) and Rampini and Viswanathan (2010). Although tangible assets are important for supporting leverage, the importance of intangible assets as collateral has been documented empirically (e.g. Mann (2015) and Lim, Macias, and Moeller (2015)).

[6]Also see Bates, Kahle, and Stulz (2009) for evidence that greater R&D intensity leads to higher cash balances. He and Wintoki (2014) document that the sensitivity of cash holdings to R&D investments among R&D-intensive firms has increased in the last 30 years, primarily due to increased competition, which is consistent with the evidence in Thakor and Lo (2017). The large cash balances arise in our analysis because the firm raises more financing than needed for immediate investment—thus carrying extra cash for later investment—because the more the firm knows relative to the market, the more information its financing decision reveals to its competitors (e.g. Kamien and Schwartz (1978)). This justification is distinct from either precautionary or tax-related motives for holding cash. See, for example, Bolton, Chen, and Wang (2014).

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

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., offer investors a put option. The insurance 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 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 view this as intermediated finance in conjunction with market financing, because the binding precommitment in the optimal mechanism may be infeasible without an intermediary.[8]

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-enhancing R&D investments. While some existing contracts involve failure insurance for entrepreneurs, a novel normative aspect of our mechanism design is the put option sold by insiders to investors. We discuss the relationship of these options to recently proposed innovations in the biopharma industry, like FDA swaps and hedges (Philipson (2015) and Jørring et al. (2017)) and "phase 2 development insurance".

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

[8]In that sense, it is similar to Phillipon and Skreta (2012) and Tirole (2012), but reservation utilities of participants remain exogenous in our analysis.

model is staged, financing is not and equity is optimal. 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.[9] Thus, our model applies primarily to firms where such conflicts are not first-order, such as public firms or firms where the non-verifiability of interim cash balances precludes contracts with triggers based on interim state realizations.[10]

The theoretical literature on incentives, decision-making, and contracts in R&D-intensive firms is also relevant to our paper—e.g. Aghion and Tirole (1994), Bhattacharya and Chiesa (1995), and Gertner, Gibbons, and Scharfstein (1988). Our paper focuses also on 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 contribution is related to Nanda and Rhodes-Kropf (2016), who show that "financing risk"—a forecast of limited future funding—disproportionately affects innovative ventures with the greatest option values. They 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 an alternative approach, and derive a mechanism that mitigates the funding gap, regardless of market conditions.[11]

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. Section 5 concludes.

[9] 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)).

[10] 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 debt and equity in the private markets—some of it through venture capital—and exhibit empirically-documented underinvestment in R&D.

[11] 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.

2 The Model

To facilitate expositional flow, we provide formal expressions of parametric restrictions in the Appendix.

2.1 Firms and Investment Decisions

Firms and Agents: There are three dates: $t = 1$, $t = 2$, and $t = 3$. All agents are risk neutral and the riskless rate is zero. There are R&D-intensive firms, each with no assets in place or cash at the beginning, date $t = 1$. 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 of $\Lambda \in \mathbb{R}_+$ at $t = 3$ if held until $t = 3$. These assets, if liquidated at $t = 1$, can be used by the insiders to self-finance the necessary investment in R&D that the firm needs to make at $t = 1$. However, because these personal assets are illiquid, they will fetch only $l\Lambda$ if liquidated at $t = 1$, where $l \in (0, 1)$. Thus, absent personal asset liquidation, R&D financing must be raised from external financiers. We assume that the deadweight cost of liquidation makes it impossible for insiders to raise *all* of the financing through personal-asset liquidation.

We refer to the insiders as the "manager". 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 ωR in capital at $t = 1$ to invest in R&D to develop a new idea, and do exploratory research, including clinical trials, where $\omega \in (0, 1)$ and $R > 0$. If the exploratory research financed by ωR delivers good results, the firm may make a bigger subsequent investment of R in R&D at $t = 2$; otherwise, it will cease further investment. The initial investment of ωR does not produce any cash flow. Its value lies solely in allowing further (bigger) investment at $t = 2$ and revealing its payoff prospects. This setup mimics the staged R&D investment process in R&D-intensive firms, with each stage requiring more resources. We will assume throughout that $[1 + \omega]R$ is much larger than Λ, so even if all personal assets are liquidated, significant external financing will be required.

Let $q \in (0,1)$ be the probability at $t = 1$ that the initial R&D will yield good results (G) and $1-q$ the probability of bad results (B) at $t = 2$. With good results, investing R at $t = 2$ will generate a probability $\delta \in (0,1)$ of achieving a high cash flow distribution, i.e., the date $t = 3$ cash flow x will have a cumulative distribution function H with support $[x_L, x_H]$ and $x_L > R[1+\omega]$) and a probability $1-\delta$ of achieving a low cash flow distribution L with support $[0, x_L]$. In addition to the cash flow x, investing R also generates non-cash assets with a random value $\tilde{A}$ at $t = 3$ that is correlated with R&D success. These assets could include patents, equipment, etc.[12] Conditional on $x \sim (x_L, x_H]$, $\tilde{A} = A > 0$ with probability r and $\tilde{A} = 0$ with probability $1-r$, where $r \in [r_a, r_b] \subset [0,1]$. Further, $\tilde{A} \equiv 0 \, \forall \, x \notin (x_L, x_H]$.

Let $\overline{G}$ be the expected value produced by the R&D in the good state:

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

We assume that $\overline{G} > R[1+\omega]$. If the R&D yields bad results (failure), then any investment at $t = 2$ leads to a zero cash flow almost surely at $t = 3$. We assume that investing ωR at $t = 1$ is worthwhile (Appendix Restriction 1). Further, we define

$$\Omega(r) = q\left[\overline{G} + \delta r A\right] + [1-q]R. \tag{2}$$

R&D Enhancement: Finally, if the firm invests R at $t = 2$, it can invest an additional $\triangle R > 0$ at $t = 2$, where $\triangle$ is a constant. If it does, there is a probability $r \in [r_a, r_b]$ 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 $t = 2$, then in the state in which the R&D yields good results and the firm has a high cash flow distribution (joint probability $q\delta$), there is a probability r that x will be distributed according to J

[12] For example, 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.

and a probability $1 - r$ that it will be distributed according to H, where J first-order-stochastically dominates H. This R&D-enhancement can be interpreted as revelation of additional commercial applications of the R&D. 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.[13]

Conditional on $x > x_L$, non-cash assets have a value A with probability r and a value 0 with probability $1 - r$, with $\tilde{A} \equiv 0$ for $x \leq x_L$. If the firm has the cash to invest R and $\triangle R$ in R&D but chooses not to do so at $t = 2$, the cash will be kept idle until $t = 3$. All three distributions—L, H, and J—have associated continuous density functions that are strictly positive over their supports. The mean cash flows associated with L, H, and J are μ_L, μ_H, and μ_J, respectively.

The role of the non-cash assets with value $\tilde{A}$ is similar to the role of assets in place in Myers and Majluf (1984). This is because the expected value of these non-cash assets is increasing in r, and r is private information for the firm. Thus, when the firm has to issue securities to finance the R&D enhancement $\triangle R$, it will worry about the dilution that accompanies any pooling outcome.

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 $t = 3$. The firm invests ωR in the first-stage R&D at $t = 1$. At $t = 2$, the manager privately observes whether the first-stage R&D produced a good or a bad outcome at $t = 2$, based on which additional debt and/or equity may be raised to invest R in the second-stage R&D at $t = 2$.

[13] One example is Botox, which 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.

Consider now the firm's incentive to raise $\triangle R$ at $t = 2$. We assume that, evaluated at $\bar{r}$, the prior belief about r, the payoff-enhancement R&D investment has negative NPV, but it has positive NPV for r high enough (Appendix Restriction 2).

2.3 Informational Frictions

The model has three frictions: asymmetric information about the upside potential of R&D, non-pledgeability of interim cash flows/balances, and risk-shifting. For simplicity, we assume no taxes. In an extension, 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.[14]

Asymmetric Information about R&D Upside Potential: Firms seeking financing are heterogeneous with respect to r—each firm's manager knows r, but others do not. 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.

Non-pledgeability of Interim Cash: Only the cash flows at $t = 3$ can be pledged by the firm to pay financiers.

Risk Shifting: The firm can unobservably switch at $t = 2$ to a negative-NPV R&D investment that requires an investment of R at $t = 2$ and pays off x with cdf M with probability $k \in (0, 1)$ and zero with probability $1 - k$. The support of M is $[0, \infty]$ and

[14] We also discuss how introducing additional benefits of debt will not change this conclusion.

$\int_0^\infty x\, dM \equiv \mu_M < R$. Such risk shifting is especially important in R&D-intensive firms—the technical nature of R&D and the relatively low probabilities of project success make it more difficult to detect this risk shifting for R&D projects than other projects.[15]

2.4 Competitive Entry

Competitive entry affects R&D profitability. A competitor may enter at either $t = 1$ or $t = 2$. If a competitor enters, then even conditional on a good first-period R&D outcome, the second-period R&D is less profitable—the payoff distribution H vanishes and each firm's cash flow is driven with probability 1 by the distribution L.

Even if no competitor entered at $t = 1$, if it becomes publicly known at $t = 2$ that the first-stage R&D yielded good results, then any new competitor can expend a cost $e > 0$ to learn about the idea and enter at $t = 2$ to invest R in second-stage R&D.[16] We assume that a competitor can raise this financing and be willing to do so—the upside potential of the R&D is high enough to make the investment positive-NPV for a potential competitor to enter, but only if it is known that the first-stage R&D succeeded (Appendix Restriction 3).

Without loss of generality, we assume henceforth that there is no competitive entry at $t = 1$, i.e., the firm in question is the only one that initially comes up with the idea. This means that a competitor will incur the private cost e and raise R to invest in R&D at $t = 2$ if it knows that the first-stage R&D produced good results, but not unconditionally. The results are qualitatively unaffected if competitive entry occurs with some exogenous probability at $t = 1$.

[15] In a security design framework with moral hazard, Babenko and Mao (2016) show that the optimal managerial compensation contract creates risk-shifting incentives that end up making debt less liquid than equity. Such liquidity differences do not play a role in our analysis.

[16] For example, the successful completion of research on the human genome project—the results of which were publicly released—allowed a proliferation of biotech companies in the marketplace. As another example, the Hatch-Waxman bill of 1984 made it easier for generics to enter the biopharma marketplace by skipping initial trials if someone had previously proven efficacy (Grabowski (2007) and Thakor and Lo (2017)).

2.5 Timeline of Events and Model Features

Figure 2 summarizes the timeline of events, the actions of the players, as well as who knows what and when. Formally this is a game 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]

3 Analysis

We now examine financing the firm will raise at $t = 1$, and then the firm's optimal financing mix at $t = 1$. The equilibrium concept is a competitive Bayesian Perfect Nash equilibrium is one in which the informed manager makes decisions to maximize the expected wealth of the firm's initial owners.

3.1 Financing Amount and Excess Cash

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

The intuition is that the firm does not want to raise additional capital at $t = 2$ because this signals project success not only to the market, but also to its competitors, reducing the firm's profit (e.g. Kamien and Schwartz (1978)). Thus, the firm will optimally want to raise all of its necessary capital earlier, when it knows less about the potential success of its R&D, and its financing is less informative. This provides a justification for the large cash balances of R&D-intensive firms that is distinct from either precautionary or tax-related motives for holding cash.

3.2 The Equity-Debt Choice and Underinvestment

If the firm chooses debt financing and does not raise $\triangle R$, it will raise $[1+\omega]R$ at $t=1$ and the expected value of its repayment obligation D_R is:

$$\mathbb{E}\left[D_R\right] = [1+\omega]R \tag{3}$$

assuming that $\triangle R$ is also raised at $t=1$.

Now consider equity. Let f be the fraction of ownership that the manager sells to investors to raise $[1+\omega]\,R$, and let $d \in \{i,n\}$ be the firm's decision d to either issue (i) or not issue (n) securities to raise financing. That is, assume initially that $\triangle R$ is not raised. Recalling that $\overline{r} = \mathbb{E}\left[r\right]$ (prior belief about r), the manager solves:

$$\max_{d}\,[1-f]\,\Omega(r), \tag{4}$$

subject to:

$$f\Omega\left(\overline{r}\right) = [1+\omega]\,R, \tag{5}$$

$$\Omega\left(\overline{r}\right) \;\; \equiv \;\; q\left[\overline{G} + \delta\overline{r}A\right] + [1-q]\,R, \tag{6}$$

and

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

If no financing is raised, $[1-f]\Omega\left(\overline{r}\right)$ in (4) is zero. So $d=i$ if, given (5), (6), and (7), the objective function in (4) is strictly positive. This maximization assumes that with equity, there will be no investment in the risk-shifting project. The following result establishes this.

Lemma 1: *If all financing is raised with equity, the manager never invests in the risk-shifting project. If all financing is raised with debt, the manager always invests in the risk-shifting project if the first-period R&D outcome is bad and R is kept idle absent the risk-shifting* *investment.*

The intuition is straightforward. With equity, the manager gets a strict proportional share of the terminal payoff, which is higher if cash is idled after a bad R&D outcome. With debt, idling the cash yields the manager zero since the debt repayment exceeds R, whereas risk-shifting yields a positive expected payoff.

Proposition 2: *The firm chooses to raise $R[1+\omega]$ at $t=1$ using only equity financing. Assuming $R[1+\omega]$ is sufficiently large, all firms raising financing are pooled at the same valuation in the market, regardless of r. For A sufficiently large, regardless of whether financing is raised through debt or equity, no firm raises $\triangle R$ in equilibrium, and any firm attempting to raise $\triangle R$ (off the equilibrium path) is believed by investors to have $r = r_a$ with probability one.*

Lemma 1 and Proposition 2 make the following points. First, debt financing is avoided, in order to eliminate risk shifting. Even if insiders offer to use personal assets as collateral for a secured loan, the proof shows that debt financing is dominated by equity financing because avoiding risk shifting with personal collateral involves a dissipative cost that is not encountered with equity. Second, 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 imposes too large a cost to induce the highest-r firm to signal.

Finally, with pooling, no firm raises $\triangle R$ in equilibrium, because doing so dilutes the claim of insiders against the non-cash assets produced by investing R.[17] This non-cash asset, with random value $\tilde{A}$, is not dependent on whether the firm invests $\triangle R$, but its expected value rA depends on the probability r, which the firm knows privately. By raising financing $\triangle R$ at a pooling price, firms with high values of r dilute the claims of their insiders against

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

$\tilde{A}$, something that can be avoided by not investing $\triangle R$ and foregoing the opportunity to enhance the payoff distribution from H to J. The dilution of insiders' claims exists with both equity and risky debt, so the underinvestment cannot be avoided.[18]

3.3 Extension: Benefits of Debt

In our base model, there is an inefficiency with debt, but the documented benefits of debt are absent. For example, one of the most-discussed benefits of debt is the debt tax shield. However, 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 be below the level that triggers risk shifting.[19] Thus a small amount of debt may be used in equilibrium, but our main analysis will be qualitatively unaffected since market-based financing still leaves underinvestment in R&D.

Formally, let τ be the corporate tax rate. Then we have:

Proposition 3: *Assume the loss in value from risk-shifting is sufficiently large. Then with corporate taxes, the debt used by the firm will be less than R, and equity financing will be used for the rest of the financing,* $R[1+\omega]$. *However, no firm will raise* $\triangle R$, *so the underinvestment in R&D will persist.*

The intuition is that the maximum debt the firm can use is limited by the amount that triggers risk shifting. This much debt will be used because the expected value of the debt tax shield is positive at this level, albeit diminished by the R&D tax shield. Nonetheless, the underinvestment in R&D persists, for the reasons discussed following Proposition 2. That is, since the firm chooses not to invest $\triangle R$ with all-equity as well as all-debt financing, it also avoids it with any mix of debt and equity.

[18] This underinvestment will also persist with convertible debt, even though convertibles may avoid the risk-shifting with straight debt.

[19] Another potential benefit of debt is monitoring. However, the monitoring benefit of debt is likely to be small as well because the highly technical nature of R&D can make it difficult for creditors to prevent risk shifting.

4 Financial Intermediation Mechanism

We previously derived conditions under which equity is the preferred market financing. Although some debt is used when taxes are introduced, regardless of the method of market financing, one friction was left unresolved—no firm chose to invest $\triangle R$, even though doing so would be valuable for some firms.[20] This raises the question: is there a mechanism beyond straight market financing that may improve outcomes? In addressing this question, no generality is lost by assuming $\tau = 0$, given Proposition 3.

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

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 any general menu must be of the form $\{\mathcal{F}(r), \wp(r), \Re(r), \pi(r)\}$, where, contingent on a report of r, the firm: (1) receives financing terms of $\mathcal{F}(r)$ when it raises financing; (2) has a "penalty" of $\wp(r)$ 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.

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

From standard arguments, it follows that the financing terms $\mathcal{F}(r)$ will be such that the cost of financing for the firm is decreasing in r. To achieve 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 will show that a general scheme like this can be implemented with *options*. Specifically, the intermediary asks the firm to sell to the equity investors it raises financing from a *put option* with a strike price of $\zeta(r)$ and also attach to it a digital option that switches on and off according to the realized value of x. The digital option causes investors to be long in the put and the firm's manager short in the put when $x \in [x_L, x_H]$, and the manager long in the put and investors short in the put when $x < x_L$. We will see that the strike price ζ lies in the interval (x_L, x_H). This means that when $x \in [x_L, x_H]$, investors exercise their put option if $\zeta > x$ and receive $\zeta - x$. When $x < x_L$, the manager exercises his put option and receives $\zeta - x$. *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 a precommitment to the intermediary's scheme, which may be unavailable with market financing. Absent such 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:

$$\Psi : [r_a, r_b] \to \mathbb{R}_+ \times [0, 1] \,. \tag{8}$$

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 $P(\tilde{r} \mid r)$ be the value of the put option 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 $[1 + \omega + \triangle] R$ at $t = 1$. We rely on our previous result that equity dominates debt in the external financing pecking order.

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. Because of the deadweight loss associated with managers liquidating their own assets to cover the cost of the put option, in the first best, no firm writes a put option, and relies solely on equity financing with no underinvestment.

Each firm's manager maximizes:

$$[1 - f(r)]\, \Omega(r) \,, \tag{9}$$

subject to:[21]

$$\Omega(r) = q\left\{\hat{G} + \delta r\left[\mu_J - \mu_H\right]\right\} + [1-q][R+\triangle], \tag{10}$$

$$f(r)\Omega(r) = [1+\omega+\triangle]\, R. \tag{11}$$

In the program above, $[1-f]\Omega(r)$ is the fraction of firm value captured by the manager ((9)), with $\Omega(r)$ being defined in (10), and

$$\hat{G} \equiv \delta\mu_H + [1-\delta]\mu_L. \tag{12}$$

Note that (10) recognizes that if the first-period R&D fails, the case $R+\triangle$ stays idle until $t=3$.

4.2 Analysis of the Mechanism

We start by noting that the first best 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 $U(\hat{r} \mid r)$ be the expected payoff of a firm with a true parameter r that reports $\hat{r}$ under the mechanism. Recalling the $l \in (0,1)$ is the fraction of illiquid assets that can be liquidated, with asymmetric information, the intermediary's problem can be expressed as

[21] To obtain (10), note that

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

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 $\hat{G} \equiv \delta\mu_H + [1-\delta]\mu_L$. That is, $\overline{G} = \hat{G}[1-\tau]$, where $\overline{G}$ is defined in (1).

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

$$\max \int_{r_a}^{r_b} \pi(r) \left\{ \Omega\left(r\right) - P(r) l^{-1} - \Omega^* \right\} z(r)\, dr, \tag{13}$$

subject to

$$\Omega\left(r, \triangle\right) = q\beta(r) + [1-q][R+\triangle], \tag{14}$$

$$\beta(r) \equiv \delta r\left[\mu_J - \mu_H\right] + \overline{G} + \delta r A, \tag{15}$$

$$U\left(\tilde{r} \mid r\right) = \pi\left(\tilde{r}\right) \left\{ \left[1 - \tilde{f}\right] \Omega\left(r\right) - P_0\left(\tilde{r} \mid r\right) l^{-1} \right\}, \tag{16}$$

$$U(r) \geq U\left(\tilde{r} \mid r\right)\ \forall r, \tilde{r} \in \left[r_a, r_b\right], \tag{17}$$

where P is the value of the put option at $t = 1$, and with $\tilde{f} \equiv f\left(\tilde{r}\right)$ being determined by:

$$\tilde{f} \Omega\left(\tilde{r}\right) + P\left(\tilde{r}\right) = \left[1 + \omega + \triangle\right] R, \tag{18}$$

and $U\left(r \mid r\right) \equiv U(r)$. Note that (14) recognizes that $R + \triangle$ stays idle until $t = 3$ if the first-period R&D fails. Also 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 intermediary maximizes the incremental surplus from mechanism design relative to the market financing outcome.

In (13) the intermediary maximizes the expectation (taken with respect to r that the intermediary does not know) of the total value of the firm Ω minus the deadweight cost of the put option Pl^{-1}, minus the value Ω^* attainable with market financing. (14) is simply the firm value when the firm's true parameter is r and it reports $\tilde{r}$. (17) is the global incentive compatibility (IC) constraint, and (18) is the competitive capital market pricing constraint.

Henceforth, for simplicity, we shall assume that L, H, and J are all uniform. The put option value (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 $\tilde{r}$ is given by:

$$\begin{aligned} P(\tilde{r} \mid r) &= q\left[\delta[1-r]\int_{x_L}^{\zeta}[\zeta(\tilde{r})-x]\,dH-[1-\delta]\int_0^{x_L}[\zeta(\tilde{r})-x]\,dL\right]. \\ &\quad -[1-q][\zeta(\tilde{r})-R] \end{aligned} \tag{19}$$

Simplifying (19) and defining $\tilde{\zeta} \equiv \zeta(\tilde{r})$ gives:

$$P_0(\tilde{r} \mid r) = \frac{q\delta[1-r]\left[\tilde{\zeta}-x_L\right]^2}{2\left[x_H-x_L\right]} - q[1-\delta]\left[\tilde{\zeta}-\mu_L\right] - [1-q][\tilde{\zeta}-R]. \tag{20}$$

As before, $P_0(r \mid r) \equiv P_0(r)$.We shall assume henceforth that the function $\phi(r) \equiv \frac{1-Z(r)}{z(r)}$ is non-decreasing in r and bounded (Appendix Restriction 4). We also assume that l is large enough—the personal asset liquidation cost is not too high (Appendix Restriction 5).

We now present a result that converts the global IC constraint (17) into a local constraint.

Lemma 3: *The global IC constraint (17) is equivalent to:*

1. $U'(r) = \pi(r)\left[q\delta\left\{[1-f(r)]\left[\mu_J-\mu_H\right]+A\right\}+\frac{l^{-1}\delta q[\zeta-x]^2}{2[x_H-x_L]}\right]$ *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. *(17) holds where* U' *does not exist.*

This lemma permits the infinite number of constraints embedded in (17) 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 Phillipon 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 (13)–(18) is equivalent to designing the functions π and ζ to maximize:*

$$\int_{r_a}^{r_b} \pi(r)\left\{\phi(r)q\delta\left[\frac{l^{-1}\left[\zeta - x_L\right]^2}{2\left[x_H - x_L\right]} + \left[\mu_J - \mu_H\right]\left[1 - C_1(r) - \frac{P_0(r)}{\Omega(r)}\right]\right]\right\} z(r)\,dr$$
$$+\int_{r_a}^{r_b} \pi(r)\left\{\left[1+\omega+\triangle\right]R - \Omega^* - P_0(r)\right\} z(r)\,dr, \tag{21}$$

where

$$C_1(r) \equiv \frac{[1+\omega+\triangle]R}{\Omega(r)}. \tag{22}$$

.

The following result characterizes the optimal mechanism.

Proposition 4: *The optimal mechanism involves:*

1. *A put option strike price of*

$$\zeta(r) = x_L + \frac{\left[x_H - x_L\right]\left\{q\left[1-\delta\right] + \left[1-q\right]\right\} C_2(r)}{q\delta\left\{C_2(r)[1-r] - \phi(r)l^{-1}\right\}}, \tag{23}$$

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 $x < x_L$. Here

$$C_2(r) \equiv 1 + \phi(r) q \delta \left[\mu_J - \mu_H\right] \left[\Omega(r)\right]^{-1}. \tag{24}$$

2.

$$\pi(r) = \begin{cases} 1 & \text{if } r \geq r^* \in [r_a, r_b] \\ 0 & \text{otherwise} \end{cases}. \tag{25}$$

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 manager (who is 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 manager to be long the put and investors short the put when $x < x_L$. Because the probability of $x < x_L$ does not depend on r, the probability of this digital option being exercised is the same for all firms regardless of r. So it reduces the probability of personal asset liquidation equally for all managers. 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 manager. 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.

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 (manager) that there is sufficient downside protection against the failure of the R&D that it is worth undertaking it.

4.3 Interpretation and Intuition

The core intuition behind why this mechanism works can be thought of as follows. Roughly speaking, we have three ranges of R&D cash flows: very low, intermediate, and very high. The probability of achieving the very high cash flows is private information for the manager, who wants to overstate this probability. By asking firms that report higher probabilities of achieving very high cash flows to provide investors greater insurance against *intermediate* cash flows being realized, the optimal mechanism design deters such misrepresentation. Of course, since R&D outcomes are uncertain, providing such insurance is costly for the manager. To offset this cost, investors insure the manager against very low cash flows. Thus, potential underinvestment in R&D is discouraged from both the standpoint of managers underinvesting due to a high possibility of failure, and investors underinvesting due to suspicion of too low a probability of very high payoffs.

More formally, our mechanism can functionally be interpreted as an exchange of put options (insurance contracts) between investors and owner-managers. One contract is offered by managers 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.[22] 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.

The other contract is offered by investors to managers, and insures the manager against a poor cash-flow outcome in the final stage of R&D. For managers, 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 managers to undertake the R&D-enhancement, which makes their initial investment pay off even more. Investors' willingness to provide this insurance therefore also increases in the probability r because this makes the upside more likely, and thus investors are willing to pay more to enable it.

The interpretation of our mechanism as insurance contracts and guarantees corresponds to the recent financial innovations in biopharma, but also offers 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 Jørring et al. (2017) for details). 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 can attenuate adverse selection, and improve R&D outcomes.

Our mechanism highlights the value of credible precommitment to a coordinating mech-

[22] 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.

anism between firm insiders and investor. The intermediary could be a third-party like an exchange, a financial institution, or consortium of firms.[23] To the extent that existing contracts do not reflect the kind of bilateral exchange of insurance that our analysis says is optimal, the implication is that the empirically-documented underinvestment in R&D may be attenuated by augmenting the contract space with intermediary assistance.

5 Conclusion

We have developed a normative model of financing for R&D-intensive firms. The setting has adverse selection and moral hazard 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. Our base model is consistent with stylized facts about firms in this environment, namely the heavy dependence on equity financing, large amounts of cash. However, we show that market financing leads to underinvestment in R&D.

Our main analysis then examines a non-market solution to the underinvestment problem. For this analysis, we take a mechanism design approach, and show that an intermediary-designed mechanism consisting of put options resolves this friction and induces firms to undertake the additional R&D investment. The analysis also more generally highlights the 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.

[23]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.

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$t = 1$	$t = 2$	$t = 3$
• Manager privately observes whether a worthwhile R&D project is available. • A firm needs ωR for initial R&D investment at $t = 1$ and R for later investment at $t = 2$. • Manager decides whether to invest ωR in an R&D project (if there is a worthwhile one). • Firm raises financing from debt or equity • The firm's manager could also liquidate personal assets Λ at a cost as an alternative to part of the capital market financing.	• If the firm invested at $t = 1$, then with probability q the investment yields G (good results), and with probability $1 - q$ that it yields B (bad results). Manager privately observes results. • The firm may raise additional financing from debt, equity, or a mix, which could convey information about B or G to competitors who may enter at $t = 2$. • With G, firm invests R at $t = 1$. May also invest additional $\triangle R$. • With B, firm ceases further investment, unless the manager decides to invest in the risk-shifting project.	• Final R&D payoff x is observed. • If firm invested R at $t = 2$, then $x \sim H$ with probability δ and $x \sim L$ with probability $1 - \delta$. Conditional on $x \sim H$, the value of non-cash R&D assets is A with probability r and 0 with probability $1 - r$. • If firm also invested additional $\triangle R$ at $t = 2$, then high cash-flow realization (which happens with probability δ) becomes $x \sim J$ with probability r, or remains $x \sim H$ with probability $1 - r$. 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

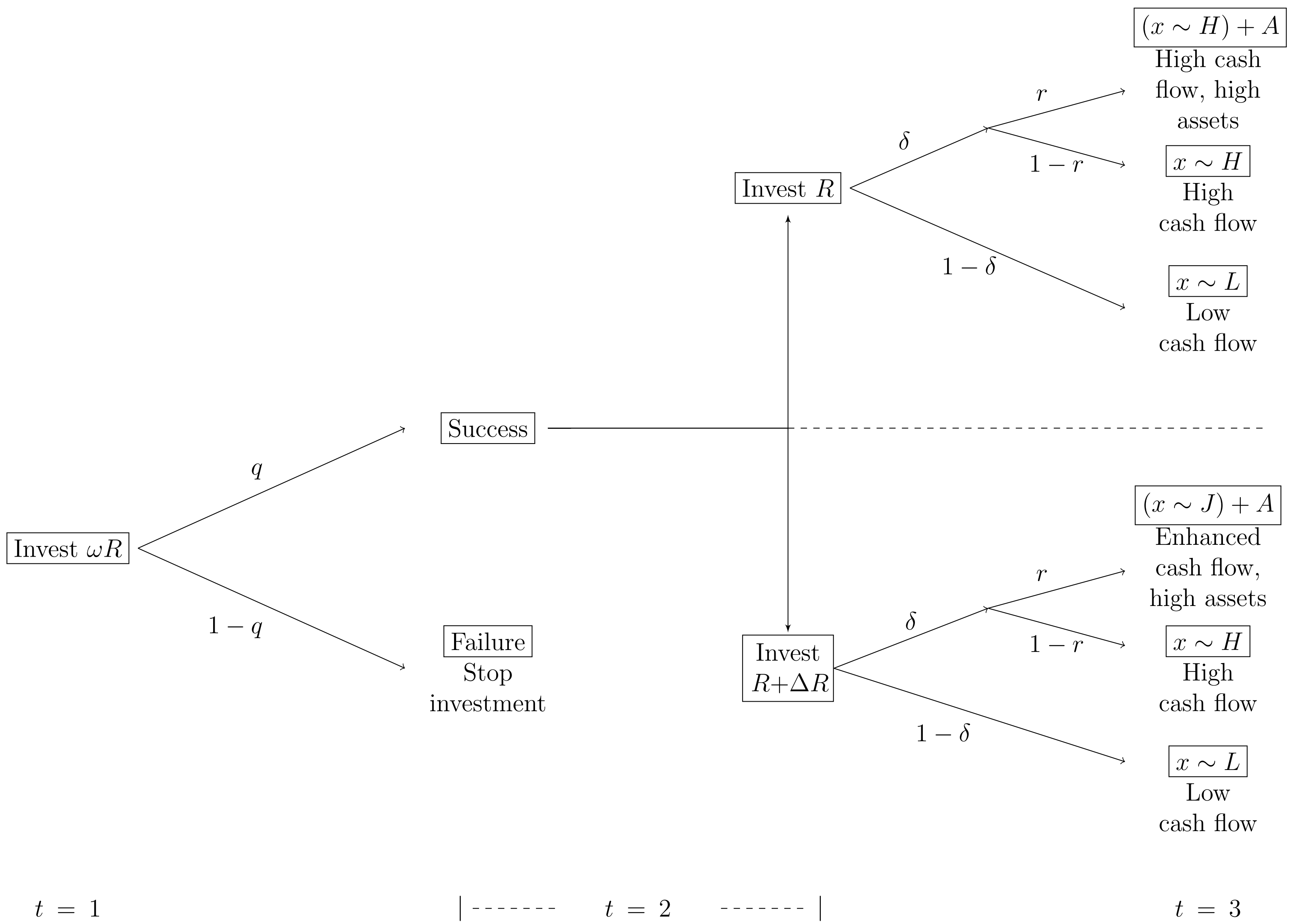

Figure 2: Summary of R&D Investment Timing (Absent Competitive Entry)

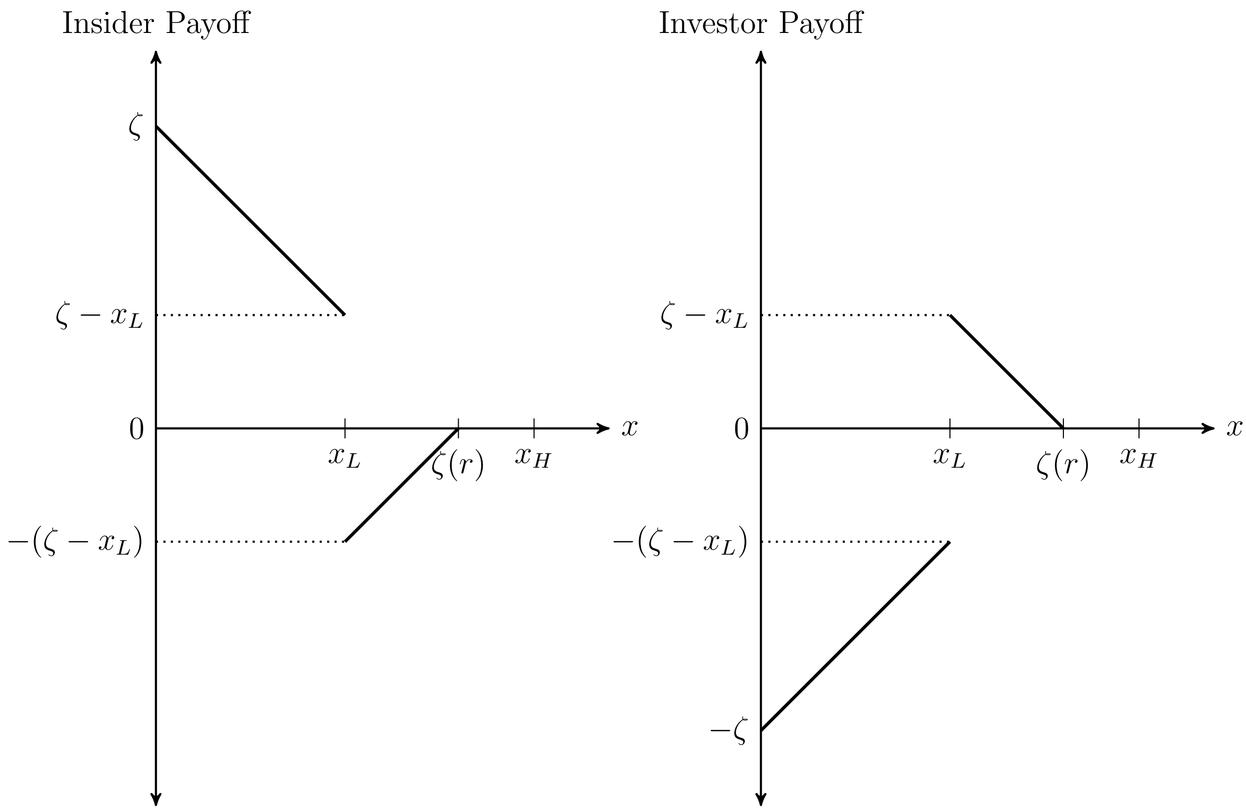

Figure 3: Mechanism Payoffs

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 A: Parametric Restrictions

We present below the formal restrictions on the parameters of the model.

Restriction 1: Investing ωR at $t = 1$ is worthwhile:

$$\omega R < q\left[\overline{G} + \delta A r - R\right] \forall r, \tag{A.1}$$

where the right-hand side (RHS) of (A.1) is the value of having the option to invest R at $t = 2$. Given (1), the firm will invest in R at $t = 2$ only if its first-period R&D yielded good results (G)—this is because the expected payoff from investing R exceeds R when the first-period R&D yields good results and is zero if the first-period R&D yields bad results.

Restriction 2: The prior belief about r has negative NPV when evaluated at $\overline{r}$, but it has positive NPV for r high enough:

$$q\delta\overline{r}\left[\mu_J - \mu_H\right] < \triangle R < q\delta r_b\left[\mu_J - \mu_H\right]. \tag{A.2}$$

Restriction 3: Competitive entry and financing conditions:

$$[\mu_L + \delta A r] = R + e + \varepsilon(r) > q\left[\mu_L + \delta A r\right] + \varepsilon(r) \,\forall r, \tag{A.3}$$

where $\varepsilon(r) > 0 \;\forall r$ and $e + \varepsilon < \omega R \;\forall r$. The left-hand side of (A.3) is the investors' assessment of the expected cash flow to a new entrant (who did not invest ωR at $t = 1$) from investing R at $t = 2$, knowing that the R&D achieved good results. The RHS is the investors' assessment when it is not known whether the R&D has produced good results.

Restriction 4: Restrictions on $\phi(r) \equiv \frac{1-Z(r)}{z(r)}$:
$\phi(r)$ satisfies $\inf_r \left\{\frac{1-r}{\phi(r)}\right\} > \sup_r \left\{l^{-1} - C_0(r)\right\} \forall r$, where:

$$C_0(r) \equiv \frac{q\delta[1-r]\left[\mu_J - \mu_H\right]}{\Omega(r)}. \tag{A.4}$$

Restriction 5: The personal asset liquidation cost is not too high:

We assume that the following sufficiency condition holds:

$$\frac{1 - r_b}{\phi(r_b)} > l^{-1} [C_2 (r_b)]^{-1} . \tag{A.5}$$

Appendix B: Proofs

Proof of Proposition 1: Suppose this were not true. Then suppose the firm knows at $t = 2$ that its first-stage R&D produced good results. If it now raises the investment R that it needs by accessing external financing. This will make it publicly known that the first-stage R&D was successful. If competitive entry occurs at $t = 2$, then the firm's *expected* project value will drop to $q[\mu_L + \delta Ar]$. Given (A.3), $\mu_L + \delta Ar = R + e + \varepsilon(r) > R + e$, so a competitor *will* enter conditional on knowing that the first-stage R&D was successful, and since $R + e > q[\mu_L + \delta Ar]$, a competitor will not enter unconditionally. Moreover, since $e + \varepsilon < \omega R$, (A.3) also implies that $q[\mu_L + \delta Ar] < R[1 + \omega]$ $\forall r$, so the firm will not make the initial investment at $t = 1$ in the first place. This means that if the firm does invest in R&D at all, it will raise the entire financing needed for the two stages, $[1 + \omega] R$, at $t = 1$, so as to avoid revealing the outcome of the first-stage R&D publicly at $t = 2$. Note that the firm raising an additional R at $t = 2$ unconditional on the first-stage R&D results is the same as raising it at $t = 1$. ■

Proof of Lemma 1: Suppose counterfacturally that the firm uses debt financing to raise $R[1+\omega]$ at $t = 1$. Then if the first-period R&D produces bad results at $t = 2$, R stays idle in the second period. Since $D_R > R$, the insiders get zero at $t = 3$ if the cash stays in the firm, and get $k \int_{D_R}^{\infty} [x - D_R]\, dM > 0$ with risk shifting. Next consider secured debt which involves insiders offering their personal assets Λ as collateral. This may deter risk shifting, but since the probability of full debt repayment is positive, the probability of inefficient asset liquidation is also positive. Since equity avoids risk shifting without asset liquidation, it dominates debt. ■

Proof of Proposition 2: The proof that the firm avoids debt and uses only equity follows from Lemma 1. The proof of the claim that the equilibrium is pooling proceeds as follows. Consider two firms, one with $r = r_a$ and the other with $r = r_b$. To ensure that the $r = r_a$ firm does not mimic the $r = r_b$ firm, the $r = r_b$ firm should liquidate a fraction $\theta \in (0, 1)$ of its insiders' assets to reduce the amount of external financing. This means $\theta l \Lambda$ is raised. The breakeven pricing condition for the $r = r_b$ firm is:

$$f_b \Omega_b = [1 + \omega]R - \theta l \Lambda, \tag{A.6}$$

where

$$\Omega_b = q\left[\overline{G} + \delta r_b A\right] + [1 - q]R. \tag{A.7}$$

Similarly, the breakeven pricing condition for the $r = r_a$ firm is:

$$f_a \Omega_a = [1 + \omega]R, \tag{A.8}$$

$$\Omega_a = q\left[\overline{G} + \delta r_a A\right] + [1 - q]R. \tag{A.9}$$

The incentive compatibility (IC) constraint is:

$$[1 - f_a]\,\Omega_a + \Lambda \geq [1 - f_b]\,\Omega_a + \Lambda[1 - \theta]. \tag{A.10}$$

Since this constraint is binding in equilibrium, we can solve (A.10) as an equality and obtain:

$$\theta = \frac{\Omega_a\,[f_a - f_b]}{\Lambda}. \tag{A.11}$$

Substituting in (A.11) from (A.6) and (A.7) and simplifying:

$$\theta = \frac{[1 + \omega]R}{\Lambda}\left\{\frac{1 - [\Omega_a/\Omega_b]}{1 - l\,[\Omega_a/\Omega_b]}\right\}. \tag{A.12}$$

If $[1 + \omega]R$ is sufficiently larger than Λ, then $\theta > 1$, making signaling infeasible.

Finally, we prove that no firm will raise $\triangle R$. Consider equity financing first. Without investing $\triangle R$, the insiders' payoff is

$$[1 - f(\overline{r})]\,\Omega(r). \tag{A.13}$$

If $\triangle R$ is raised, the payoff is

$$\left[1-\tilde{f}\left(\overline{r}\right)\right]\left\{\Omega(r)+q\delta r\left[\mu_J-\mu_H\right]\right\}. \tag{A.14}$$

Given (A.2), we know that $\tilde{f}\left(\overline{r}\right)>f\left(\overline{r}\right)$. Thus, the condition needed to ensure that no firm wishes to raise $\triangle R$ at the pooling ownership fraction $f\left(\overline{r}\right)$ is that (A.13) exceeds (A.14), where

$$\tilde{f}\left(\overline{r}\right)\left\{\Omega\left(\overline{r}\right)+q\delta\overline{r}\left[\mu_J-\mu_H\right]\right\}=[1+\omega+\triangle]R. \tag{A.15}$$

A sufficient condition for (A.13) to exceed (A.14) is that

$$A\left[\tilde{f}\left(\overline{r}\right)-f\left(\overline{r}\right)\right]>\left[1-\tilde{f}\left(\overline{r}\right)\right]\left[\mu_J-\mu_H\right], \tag{A.16}$$

which will hold for A large enough. Moreover, given the out-of-equilibrium belief stipulated in the proposition, no firm will wish to raise additional capital. Now consider debt to finance either $R[1+\omega]$ or $R[1+\omega+\triangle]$. Let $\varepsilon\left(D\left(\tilde{r}\right),r\right)$ be the expected value of equity when debt D is raised, the market prices it as if $r=\tilde{r}$ and the firm's true parameter is r. Then it is straightforward to show that $\varepsilon\left(R[1+\omega]\left(\overline{r}\right),r\right)=\left[1-f\left(\overline{r}\right)\right]\Omega(r)$ and $\varepsilon\left(R[1+\omega+\triangle]\left(\overline{r}\right),r\right)=\left[1-\tilde{f}\left(\overline{r}\right)\right]\left\{\Omega(r)+\delta r\left[\mu_J-\mu_H\right]\right\}$. The rest of the proof follows that for equity. ■

Proof of Proposition 3: Suppose, counterfactually, that the firm raises all of $R[1+\omega]$ from debt. Then, in the state in which R is kept idle because of a bad first-period R&D outcome, the firm cannot fully repay bondholders. This means debt is risky and

$$D_R>[1+\omega]R, \tag{A.17}$$

where D_R, the face value of debt that must be repaid at $t=3$, is given in (3). Now let $\varphi_L\left(D_R,[1+\omega]R\right)$ and $\varphi_H\left(D_R,[1+\omega]R\right)$ be the incomes sheltered from taxes due to debt when

$x \sim L$ and $x \sim H$ respectively. Here

$$\varphi_L \equiv \varphi_L\left(D_R, [1+\omega]R\right) = \begin{cases} \int_{[1+\omega]R}^{D_R} x\, dL + D_R\left[1 - L\left(D_R\right)\right] & \text{if } D_R < x_L \\ 0 & \text{if } D_R \geq x_L \end{cases} \tag{A.18}$$

$$\varphi_H \equiv \varphi_H\left(D_R, [1+\omega]R\right) = \begin{cases} D_R & \text{if } D_R < x_L \\ \int_{[1+\omega]R}^{D_R} x\, dH + D_R\left[1 - H\left(D_R\right)\right] & \text{if } D_R \in (x_L, x_H) \end{cases} \tag{A.19}$$

Note that these expressions recognize that for $x < R[1+\omega]$, the expensing of R&D for taxes means that all of the income is shielded from taxes even without debt, so the debt tax shield is zero. Let the expected debt tax shield be:

$$\Gamma_D = \tau q \left\{\delta \varphi_H + [1-\delta]\varphi_L\right\}. \tag{A.20}$$

It is clear that $\Gamma_D > 0$. Assume that the value loss from risk shifting is large relative to Γ_D, i.e.,

$$R - \mu_M > \Gamma_D. \tag{A.21}$$

This means it is value-maximizing for the firm to set the amount it borrows such that risk shifting does not occur. This condition is that $D_R \leq D_R^*$, where

$$[R - D_R^*] = \kappa \int_{D_R^*}^{\infty} x\, dM. \tag{A.22}$$

It is clear that if D is the amount borrowed, then $D < D_R$, and from (A.22) it follows that $D_R < R$. Thus, $D < D_R$. From Proposition 2, it follows that with debt financing, the firm will not invest $\triangle R$. ■

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

$$[1 - f_2]\,\Omega(r_1) \quad > \quad [1 - f_1]\,\Omega(r_1)\,, \tag{A.23}$$

which follows since $f_1 > f_2$. Note that $f_1 > f_2$ follows from (18) and the fact that $\Omega(r)$ defined in (14) is strictly increasing in r and the right-hand side of (A.23) is a constant. Thus, the r_1 firm will misreport its type as r_2. ■

Proof of Lemma 3: Substituting from (18) into (16), we can write:

$$\begin{aligned} U(r) &= \left[\Omega(r, \triangle) - [1 + \omega + \triangle] + P - Pl^{-1}\right]\pi(r) \\ &= \pi(r)\left[\Omega(r, \triangle) - [1 + \omega + \triangle]\,R - \left[l^{-1} - 1\right]P(r)\right]. \end{aligned} \tag{A.24}$$

We will first show that (17) implies parts 1 and 2 of the lemma. From (17) we have that $U(r \mid r) \geq U(\tilde{r} \mid r)$, so:

$$\begin{aligned} &\pi(r)\left[\Omega(r, \triangle) - [1 + \omega + \triangle]\,R - \left[l^{-1} - 1\right]P(r)\right] \\ \geq\ &\pi(\tilde{r})\left[\left[1 - \tilde{f}\right]\Omega(r, \triangle) - P(\tilde{r} \mid r)l^{-1}\right]. \end{aligned} \tag{A.25}$$

From (20) we have

$$P(\tilde{r} \mid r) = P(\tilde{r}) + \frac{q\delta\,[\tilde{r} - r]\left[\tilde{\zeta} - x_L\right]^2}{2\,[x_H - x_L]}. \tag{A.26}$$

Substituting (A.26) in (A.25) yields:

$$\begin{aligned} &\pi(r)\left[\Omega(r, \triangle) - [1 + \omega + \triangle]\,R - \left[l^{-1} - 1\right]P_0(r)\right] \\ \geq&\pi(\tilde{r})\left[\left[1 - \tilde{f}\right]\Omega(\tilde{r}, \triangle) - P_0(\tilde{r})l^{-1} - \frac{q\delta l^{-1}\,[\tilde{r} - r]\left[\tilde{\zeta} - x_L\right]^2}{2\,[x_H - x_L]} + \left[1 - \tilde{f}\right]\Omega(r, \triangle) - \left[1 - \tilde{f}\right]\Omega(\tilde{r})\right] \\ =&U(\tilde{r}) + \pi(\tilde{r})\left\{\frac{q\delta l^{-1}\,[r - \tilde{r}]\left[\tilde{\zeta} - x_L\right]^2}{2\,[x_H - x_L]} + \left[1 - \tilde{f}\right][\Omega(r, \triangle) - \Omega(\tilde{r}, \triangle)]\right\}. \end{aligned} \tag{A.27}$$

Now using (14) we see that

$$\Omega\left(r,\triangle\right)-\Omega\left(\tilde{r},\triangle\right)=q\delta\left[\mu_J-\mu_H+A\right]\left[r-\tilde{r}\right]. \tag{A.28}$$

Define

$$N\left(\tilde{r}\right)\equiv\pi\left(\tilde{r}\right)\left\{\frac{q\delta l^{-1}\left[\tilde{\zeta}-x_L\right]^2}{2\left[x_H-x_L\right]}+\left[1-\tilde{f}\right]q\delta\left[\mu_J-\mu_H+A\right]\right\}. \tag{A.29}$$

Substituting (A.29) in (A.27) gives us:

$$U(r)-U\left(\tilde{r}\right)\geq\left[r-\tilde{r}\right]N\left(\tilde{r}\right), \tag{A.30}$$

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

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

which implies

$$U(r)-U\left(\tilde{r}\right)\leq\left[r-\tilde{r}\right]N(r). \tag{A.32}$$

Combining (A.30) and (A.32) yields:

$$\left[r-\tilde{r}\right]N\left(\tilde{r}\right)\leq U(r)-U\left(\tilde{r}\right)\leq\left[r-\tilde{r}\right]N(r). \tag{A.33}$$

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

$$\lim_{\tilde{r}\to r}\frac{U(r)-U\left(\tilde{r}\right)}{\tilde{r}-r}=U'(r)=N(r)>0 \text{ almost everywhere.} \tag{A.34}$$

Since $N(r)$ is non-decreasing, it follows that $U''\geq 0$ almost everywhere. Thus we have shown that (17) implies parts 1 and 2 of the Lemma.

Next, we will show that parts 1 and 2 of the lemma imply (17). Note that

$$\begin{aligned} U(r \mid r) - U(\tilde{r} \mid r) &= U(r \mid r) - U(\tilde{r} \mid r) + [r - \tilde{r}]\, N(\tilde{r}) \\ &= \int_{\tilde{r}}^{r} U'(t \mid t)dt - [r - \tilde{r}]\, U'(r \mid \tilde{r}) \\ &\geq 0, \end{aligned} \tag{A.35}$$

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

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 2), 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 $Z(r)$), (A.2) 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. ■

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

$$\int_{r_a}^{r} U'(\tilde{r} \mid \tilde{r})\, d\tilde{r} = \int_{r_a}^{r} N(\tilde{r})\, d\tilde{r}, \tag{A.36}$$

which means

$$\begin{aligned} U(r) - U(r_a) &= \int_{r_a}^{r} N(\tilde{r})\, d\tilde{r} \\ \Longrightarrow U(r) &= U(r_a) + \int_{r_a}^{r} N(\tilde{r})\, d\tilde{r}. \end{aligned} \tag{A.37}$$

Taking the expectation of (A.37) yields:

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

where $\phi(r) \equiv \frac{[1-Z(r)]}{z(r)}$. Now we know from (16) that

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

Substituting in (A.39) for $f\Omega$ from (18) gives us:

$$\pi(r)\left[\Omega(r) - P_0(r)l^{-1}\right] = U(r) + \pi(r)\left[[1+\omega+\triangle]R - P(r)\right]. \tag{A.40}$$

Substituting (A.40) into (13) yields the objective function:

$$\int_{r_a}^{r_b}\left\{U(r) + \pi(r)\left[[1+\omega+\triangle]R - \Omega^* - P(r)\right]\right\} z(r)dr. \tag{A.41}$$

The intermediary 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.38) in (A.41) above to get

$$\overline{u}_a + \int_{r_a}^{r_b}\left\{\phi(r)N(r) + \pi(r)\left[[1+\omega+\triangle]R - \Omega^* - P(r)\right]\right\} z(r)dr. \tag{A.42}$$

Now use (A.29) and write

$$N(r) = \pi(r)\left\{\frac{q\delta l^{-1}\left[\zeta - x_L\right]^2}{2\left[x_H - x_L\right]} + [1-f]\,q\delta\left[\mu_J - \mu_H + A\right]\right\}, \tag{A.43}$$

so that, using (18) and (22), the intermediary's objective function (A.42) can be written as:

$$\overline{u}_a + \int_{r_a}^{r_b} \pi(r)\phi q\delta \left\{ \frac{l^{-1}\left[\zeta - x_L\right]^2}{x_H - x_L} + \left[\mu_J - \mu_H + A\right]\left[1 - C_1(r) + \frac{P(r)}{\Omega(r)}\right]\right\} z(r)\,dr$$
$$+ \int_{r_a}^{r_b} \pi(r)\left\{\left[1 + \omega + \triangle\right]R - P(r) - \Omega^*\right\} z(r)\,dr. \tag{A.44}$$

This completes the proof since maximizing (A.44) is equivalent to maximizing (A.44) because $\overline{u}_a$ is a constant (i.e. independent of the mechanism design functions). ■

Proof of Proposition 4: We now proceed with proving the proposition. From optimal control theory, we know that the value function ζ that maximizes (A.44) is the one that involves maximizing the integral pointwise. Thus, the first-order condition for ζ is:

$$l^{-1}\phi(r)q\delta\left[\zeta - x_L\right]\left[x_H - x_L\right]^{-1}$$
$$-C_2(r)\left\{q\delta[1-r]\left[\zeta - x_L\right]\left[x_H - x_L\right]^{-1} - q[1-\delta] - [1-q]\right\} = 0. \tag{A.45}$$

The second-order condition is:

$$l^{-1}\phi(r)q\delta\left[x_H - x_L\right]^{-1} - C_2(r)q\delta[1-r]\left[x_H - x_L\right]^{-1} < 0, \tag{A.46}$$

which holds given (A.5).

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

$$\zeta(r) = x_L + \frac{\left[x_H - x_L\right]\left\{q[1-\delta] + [1-q]\right\}}{q\delta\left\{[1-r] - \left[\phi(r)/C_2(r)\right]l^{-1}\right\}}, \tag{A.47}$$

which is (23). 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.44) also reveals that the intermediary will set $\pi = 1$ whenever the term multiplying $\pi(r)$ in (A.44) is positive and set $\pi = 0$ otherwise. Since $U'(r) > 0$ in equilibrium, it follows that $\exists\, r^*$ such that $\pi(r) = 1\ \forall\, r \geq r^*$ and $\pi(r) = 0$ otherwise. ■