Optimal Financing for R&D-Intensive Firms*

Richard T. Thakor† and Andrew W. Lo‡

This Draft: 8 December 2020

Abstract

We develop a theory of optimal financing for R&D-intensive firms. When only debt and equity financing are available, such firms rely exclusively on equity financing and carry excess cash, and underinvest in R&D. But when the feasible set of contracts is augmented to include non-linear payoff schemes, this underinvestment is reduced, and a financial intermediary can improve the welfare attainable with these schemes. We then use a mechanism design approach and show that such non-linear 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 also improves welfare in this case.

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

JEL Classification: D82, D83, G31, G32, G34, O31, O32

*We thank Asaf Bernstein, Hui Chen, Murray Frank, Xavier Giroud, Daniel Green, Dirk Hackbarth (discussant), Jack Liebersohn, Debbie Lucas, Daniel Saavedra Lux, Andrey Malenko, William Mann, Stew Myers, Jonathan Parker, David Robinson, Raj Singh, Anjan Thakor, Vijay Yerramilli (discussant), seminar participants at MIT, and conference participants at the *American Finance Association* Meetings and the *Midwest Finance Association* Meetings for helpful comments and discussions. We also thank Xuelin Li for research assistance. Any remaining errors are our own. Research support from the MIT Laboratory for Financial Engineering is gratefully acknowledged. The views and opinions expressed in this article are those of the authors only and do not necessarily represent the views and opinions of any other organizations, any of their affiliates or employees, or any of the individuals acknowledged above.

†University of Minnesota - Carlson School of Management and MIT LFE, 321 19th Avenue South, 3-255, Minneapolis, MN 55455. E-mail: rthakor@umn.edu

‡MIT Sloan School of Management, CSAIL, and NBER, 100 Main Street, E62–618, Cambridge, MA 02142

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 finance theory 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 the frictions discussed above. We lay the groundwork for our analysis by first examining a market

[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). This can happen even with risk neutrality of decision makers if R&D failure causes the firm to incur financial distress costs or suffer inefficient asset liquidation.

setting in which the firm is limited to standard debt and equity. In this setting, we establish that, under conditions typical for R&D-intensive firms, the optimal capital structure avoids debt, relying exclusively on outside equity and excess cash to finance R&D.[4] However, this generates an outcome in which all firms underinvest in incremental payoff-enhancing R&D investments. We also provide an extension of our model in which a limited amount of debt is used, due to a tax shield advantage, but the underinvestment persists. 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.[5]

The implications of our model are 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));[6] (ii) large cash balances (e.g. Brown and Petersen (2011) and Begenau and Palazzo (2016));[7] and (iii) underinvestment in R&D even by publicly-traded firms (e.g. Brown and Petersen (2011) and Hall and Lerner (2010)). This underinvestment with market financing

[4] A similar result, albeit for different reasons, appears in Fulghieri, Garcia, and Hackbarth (2020). They show that when asymmetric information is about assets in place, equity dominates debt for younger, high-growth firms.

[5] 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.

[6] 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), Lim, Macias, and Moeller (2015), and Hochberg, Serrano, and Ziedonis (forthcoming)).

[7] 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).

sets the stage for the main intended contribution of the paper.

We then turn to the more normative issue of whether the debt-equity market financing outcome can be improved upon by adding a scheme of (non-linear) rewards and penalities 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. 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.[8] 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,

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

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.[9]

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. 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.[10] 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.[11]

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)

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

[10] 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.

[11] 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.

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 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, whereas this conflict exists with debt.[12] 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 with triggers based on interim state realizations.[13]

Our paper is also 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; Ederer and Manso (2013) provide supporting experimental evidence, and Azouly, Graff Zivin and Manso (2011) provide evidence that these types of contracts also provide effective incentives for producing high-impact articles in academic life sciences. 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

[12] 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)).

[13] 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.

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.[14]

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. We conclude in Section 5. All proofs are in the Appendix.

2 The Model

To facilitate expositional simplicity, we outline the basic structure of our theoretical framework in this section and relegate formal expressions of parametric restrictions to 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 $t = 1$.[15] 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 $t = 3$ if held until $t = 3$. These assets, if liquidated at

[14] 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.

[15] This assumption is an abstraction, meant to reflect that the firm lacks sufficient collateralizable assets and cash to be able to raise all its needed financing with cash and riskless debt. The need to raise risky external financing is our starting point.

$t = 1$, 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 $l \in (0, 1)$.[16] In other words, these illiquid assets are worth more to insiders if held until $t = 3$ 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 $t = 3$, 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". 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

[16]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.

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 be viewed as assets in place, such as equipment whose value is higher when R&D succeeds.[17] 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 $q\delta$, this means that the unconditional probability of $\tilde{A} = A$ is $q\delta r$.

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 whenever $\gamma = \gamma_h$, the cash flow x will be distributed according to J, where J first-order-stochastically

[17] For example, manufacturing equipment for an existing product is often utilized to manufacture a new product that stems from successful R&D, thus increasing the value of the existing products. Examples of these assets may also include early-stage patents. 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.

dominates H. In other words, conditional on investing $\triangle R$, the ex ante probability is $q\delta r$ that the distribution of x is J and $q\delta[1-r]$ that the distribution of x is 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.[18]

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. We assume that these assets are non-pledgeable for securing financing.

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

[18] 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.

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 $t = 2$.

Consider now the firm's incentive to raise $\triangle R$ at $t = 2$. 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 (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.[19]

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 $\overline{r}$. 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.

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

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 $\int_0^\infty x\, dM \equiv \mu_M < R$. 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.[20]

2.4 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]

The equilibrium concept is a competitive Bayesian Perfect Nash equilibrium in which the informed manager makes decisions to maximize the expected wealth of the firm's initial owners.[21] Specifically, the informed manager moves first at $t = 1$ by choosing to raise financing ωR with debt or equity (or a mix), 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. The manager privately observes the results of the first-stage R&D and then decides to raise an additional R or $R + \triangle R$ at $t = 2$. Investors update their beliefs further and use the updated beliefs to price the securities they purchase at $t = 2$. If the firm's choices are along the path of play, investors use Bayes Rule to revise their beliefs.

[20]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.

[21]By competitive, we mean that securities are priced to yield investors an expected return of zero.

3 Analysis

We now examine financing the firm will raise at $t = 1$, and then the firm's optimal financing mix at $t = 1$. In this section, we focus on debt and equity financing raised in the capital market. Let $T_E(E)$ and $T_D(D)$ be the transactions costs of raising equity E and debt D, respectively, with $T_E^{'} = T_D^{'} > 0$, $T_E(0) = \overline{T}_E > 0$, and $T_D(0) = \overline{T}_D > 0$. That is, the transactions costs of raising external financing have both fixed-cost and variable-cost elements.

3.1 Financing Amount and Excess Cash

Lemma 1: *Regardless of whether financing is raised via debt or equity, 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* $t = 2$*.*

This result follows immediately from the assumption that capital raising has a fixed cost, as it is better to raise all the capital that is needed at the outset.

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 $\overline{r} = \mathbb{E}[r]$ (prior belief about r), the manager solves:

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

subject to:

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

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

and

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

If no financing is raised, $[1-f]\Omega(\overline{r})$ 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 2: *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. Thus, if $T_E(x) - T_D(x)$ is small relative to the loss from risk shifting, the firm will prefer equity over debt.

Proposition 1: *Assuming $R[1+\omega]$ is sufficiently large, all firms raising equity financing are pooled at the same valuation in the market, regardless of r, even when signaling with inside ownership is allowed. For A sufficiently large, regardless of the firm's capital structure (i.e.*

whether financing is raised through debt or equity or some mix), 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.

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 dilutes the claim of insiders against the non-cash assets produced by investing R.[22] 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 $\tilde{A}$, 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, regardless of the firm's capital structure choice.[23]

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

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

[23]It can also be formally shown that the underinvestment will also persist with convertible debt, even though convertibles may avoid the risk-shifting with straight debt.

feasible debt will be below the level that triggers risk shifting.[24] 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, we introduce one additional element: let τ be the effective corporate tax rate.

Proposition 2: *Let $R - \mu_M$ be sufficiently large. Then there exists a cut-off value of the effective tax rate, say $\hat{\tau}$, such that the firm will be all-equity financed if $\tau \leq \hat{\tau}$ and will have a mix of debt and equity if $\tau > \hat{\tau}$.*

The intuition is as follows. The firm would like to maximize its use of leverage due to the debt tax shield. But it also wants to avoid a situation in which the amount of debt is so high that it induces the firm to raise financing even with first-period R&D failure and then engage in risk shifting. If the debt raised exceeds this risk-shifting trigger level of debt, bondholders will price this inefficiency in the repayment they demand. This means the cost of risk shifting is borne by the firm's insiders in equilibrium, and when this cost is high, it is avoided by limiting debt to be no higher than the trigger level. This will limit the debt tax shields the firm can enjoy. Moreover, the tax deductibility of R&D outlays also reduces the value of debt tax shields. When the firm's effective tax rate is low, the value of debt tax shields falls below the transaction cost of raising debt, so the firm is all-equity financed. Otherwise, the firm uses debt equal to the trigger level above which risk shifting is triggered, so both debt and equity are present in its capital structure.

The risk-shifting problem with debt leads to a conflict between the firm's insiders and bondholders on the R&D continuation decision in the (privately observed) bad state at $t = 1$. The bondholders would like the firm to cease R&D, whereas insiders want to inefficiently continue, unless the amount of debt is sufficiently low. Such a continuation conflict does not exist with equity, so under some conditions, the firm uses only equity.[25] However, it

[24] 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.

[25] We are not the first to indicate that the Myers and Majluf (1984) pecking order could be reversed under

should be emphasized that the result in Proposition 2 still holds—underinvestment persists regardless of the firm's capital structure.

3.4 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.[26] 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 Non-linear Financing Mechanism with an Intermediary

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

some conditions. For example, Halov and Heider (2011) argue that asymmetric information about the risk of investments can lead to equity being preferred to debt in the pecking order. See also Nachman and Noe (1994) and Spiegel and Ravid (1997).

[26]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.

so would be valuable for some firms.[27] 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, and assuming that all market financing is done with equity.[28]

To explore this, we expand the feasible set of contracts beyond debt and equity 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

[27] 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.

[28] That is, we assume that the condition for all-equity financing in Proposition 3 holds. As previously noted, the underinvestment problem persists with both debt and equity, and therefore it is simplest to assume all-equity financing for the purposes of the mechanism design analysis.

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.

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.[29] 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.[30] Because of the deadweight loss associated with managers liquidating

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

[30]This is a first best in the sense that investors know each firm's r and price securities accordingly in a competitive market.

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.

Each firm's manager maximizes:

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

subject to:[31]

$$\Omega\left(r,\triangle\right)=q\left\{\hat{G}+\delta r\left[\mu_J-\mu_H\right]\right\}+[1-q][R+\triangle R], \tag{9}$$

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

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

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

Note that (9) recognizes that if the first-period R&D fails, the case $R+\triangle$ stays idle until $t=3$.

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

[31] To obtain (9), note that

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

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).

is a straight equity contract in which

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

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 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 $f\left(r_b\right)$ as the ownership fraction sold by the firm reporting $r=r_b$ to raise $[1+\omega+\triangle]\,R$ in financing, if $\varphi\left(r_b\right)<\left[1-f_{r_b}\right]x_L$, 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:

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

where $f\left(r_b\right)$ satisfies

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

Solving (14) and (15) simultaneously yields

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

More Severe Adverse Selection: It is apparent from (16) that $\partial\varphi/\partial\Omega\left(r_b, \triangle\right) > 0$, so φ increases as adverse selection worsens. At some point, for $r_b - r_a$ sufficiently high, incentive compatibility will demand $\varphi\left(r_b\right) > \left[1 - f\left(r_b\right)\right] x_H$. This will require the firm that reports $r = r_b$ to liquidate its illiquid asset to pay $\varphi\left(r_b\right)\ \forall\, x \in [x_L, x_H]$.

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 $\Omega\left(r_b\right)$ 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, $\Re\left(r_b\right)$ 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

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

$$V_L \equiv q[1-\delta]\mu_L + [1-q][R + \triangle R] \tag{19}$$

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

Now, a firm reporting $r = r_b$ will raise the necessary financing, $[1 + \omega + \triangle] R$, 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

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

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

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

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

This now leads to:

Lemma 3: *The optimal penalty is:*

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

where

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

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

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

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 $x < x_L$.

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:

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

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:

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

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

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

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

The IC constraint is:

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

This now leads to the following result:

Proposition 3: *The optimal penalty structure with an intermediary is:*

$$\overline{\varphi}\left(r_b\right)=\frac{[1-l]\mu_H}{U_1}+\frac{\left[1+\omega+\triangle\right]RU_2}{U_1}+\frac{\kappa V_L[1+m]}{U_1q\delta\left[1-r_b\right]}+\frac{\hat{a}_b[1-\kappa]V_L}{U_1q\delta\left[1-r_a\right]l^{-1}} \tag{33}$$

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

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.[32] The proposition also says that when intermediation is sufficiently valuable, giving insiders 100% ownershio of the cash flows when $x < x_L$ 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.[33]

[32]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)).

[33]The reason why intermediation needs to be sufficiently valuable (which is a sufficiency condition) is that

5 Implementing the Mechanism with Options: A Mechanism Design Approach

5.1 Preliminaries

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 $[r_a, r_b]$.

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 $x \in [x_L, x_H]$.[34] 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 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

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.

[34] 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.

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 $[1 + \omega + \triangle] R$ 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 4: *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:

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

subject to

$$\Omega\left(r, \triangle\right) = q\beta(r) + [1-q][R + \triangle R] \equiv \hat{\Omega}(r, \triangle) + V_L + V_H, \tag{37}$$

$$\beta(r) \equiv \delta r \left[\mu_J - \mu_H\right] + \overline{G} + \delta r A, \tag{38}$$

$$U\left(\tilde{r} \mid r\right) = \pi\left(\tilde{r}\right) \left\{ \left[1 - \tilde{f}\right] \hat{\Omega}\left(r, \triangle\right) - P_0\left(\tilde{r} \mid r\right) l^{-1} + P_I\left(\tilde{r} \mid r\right) + V_L \right\}, \tag{39}$$

$$U(r) \geq U\left(\tilde{r} \mid r\right) \;\; \forall r, \tilde{r} \in \left[r_a, r_b\right], \tag{40}$$

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 $\tilde{f} \equiv f\left(\tilde{r}\right)$ being determined by:

$$\tilde{f} \hat{\Omega}\left(\tilde{r}\right) + V_H\left(\tilde{r}\right) + P_0\left(\tilde{r}\right) - P_I\left(\tilde{r}\right) = \left[1 + \omega + \triangle\right] R, \tag{41}$$

and $U\left(r \mid r\right) \equiv U(r)$. Note that (37) 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 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. (40) is the global incentive compatibility (IC) constraint, and (41) 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:

$$P_0(\tilde{r} \mid r) = q\delta[1-r]\int_{x_L}^{\zeta(\tilde{r})} [\zeta(\tilde{r}) - x]\ dH, \tag{42}$$

$$P_I(\tilde{r} \mid r) = q[1-\delta]\int_0^{x_L} [\zeta(\tilde{r}) - x]\ dL + [1-q]\left[\zeta(\tilde{r}) - R - \triangle R\right]. \tag{43}$$

Simplifying (42) and (43) and defining $\zeta(\tilde{r}) = \tilde{\zeta}$ gives:

$$P_0(\tilde{r} \mid r) = \frac{q\delta[1-r]\left[\tilde{\zeta} - x_L\right]^2}{2\left[x_H - x_L\right]}, \tag{44}$$

$$P_I(\tilde{r} \mid r) = q[1-\delta]\left[\tilde{\zeta} - \mu_L\right] + [1-q]\left[\tilde{\zeta} - R - \triangle R\right]. \tag{45}$$

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 3). We also assume that l is large enough—the personal asset liquidation cost is not too high (Appendix Restriction 4).

We now present a result that converts the global IC constraint (40) into a local constraint.

Lemma 5: *The global IC constraint (40) is equivalent to:*

1. $U'(r) \equiv N(r) = \pi(r)\left[q\delta\left\{[1-f(r)]\left[\mu_J + A\right]\right\} + \frac{l^{-1}\delta q[\zeta - x]^2}{2[x_H - x_L]}\right]$ *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. *(40) holds where* U' *does not exist.*

This lemma permits the infinite number of constraints embedded in (40) to be replaced with conditions involving the first and second derivatives of U.

We can now show:

Lemma 6: *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 7: *The regulator's mechanism design problem in (36)–(41) is equivalent to designing the functions π and ζ to maximize:*

$$\int_{r_a}^{r_b} \pi(r) \left\{ \phi(r) q\delta \left[\frac{l^{-1} \left[\zeta - x_L\right]^2}{2 \left[x_H - x_L\right]} + \left[\mu_J + A\right] \left[1 - C_1(r) - \frac{P(r)}{\hat{\Omega}(r)} \right] \right] \right\} z(r)\, dr$$
$$+ \int_{r_a}^{r_b} \pi(r) \left\{ \left[1 + \omega + \triangle\right] R - \Omega^* - P(r) \right\} z(r)\, dr, \tag{46}$$

where

$$C_1(r) \equiv \frac{[1 + \omega + \triangle] R - V_H}{\hat{\Omega}(r)}. \tag{47}$$

.

and

$$P(r) \equiv P_0(r) - P_I(r). \tag{48}$$

The following result characterizes the optimal mechanism.

Proposition 4: *The optimal mechanism involves:*

1. *A put option strike price of*

$$\zeta(r) = x_L + \frac{[x_H - x_L]\,\{q\,[1-\delta] + [1-q]\}\,C_2(r)}{q\delta\,\{C_2(r)[1-r] - \phi(r)l^{-1}\}}, \tag{49}$$

   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

$$C_2(r) \equiv 1 + \phi(r)q\delta\,[\mu_J + A]\left[\hat{\Omega}(r)\right]^{-1}. \tag{50}$$

2.

$$\pi(r) = \begin{cases} 1 & \textit{if } r \geq r^* \in [r_a, r_b] \\ 0 & \textit{otherwise} \end{cases}. \tag{51}$$

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.[35]

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 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.

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

[35]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.

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.[36] 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.

The interpretation of our mechanism as insurance contracts and guarantees also corresponds to the recently proposed 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 Jorring

[36]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.

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 in conjunction with equity can attenuate adverse selection, and improve R&D outcomes.

5.4 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.[37]

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.[38] 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.

[37] We do not provide these details here, but they are available upon request.

[38] 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.

6 Conclusion

Using mechanism design theory, 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. However, 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. The analysis thus 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.

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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

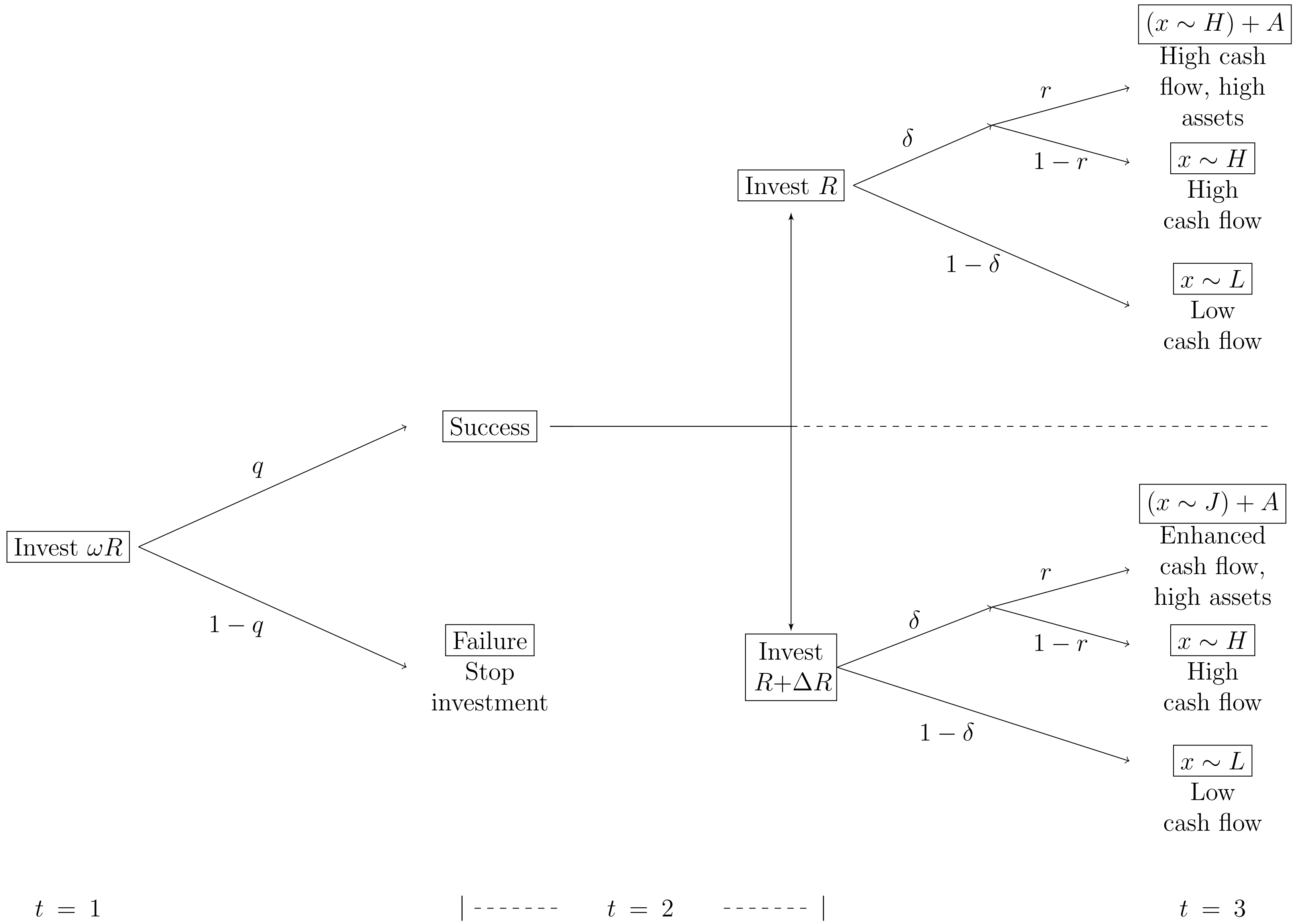

Figure 2: Summary of R&D Investment Timing

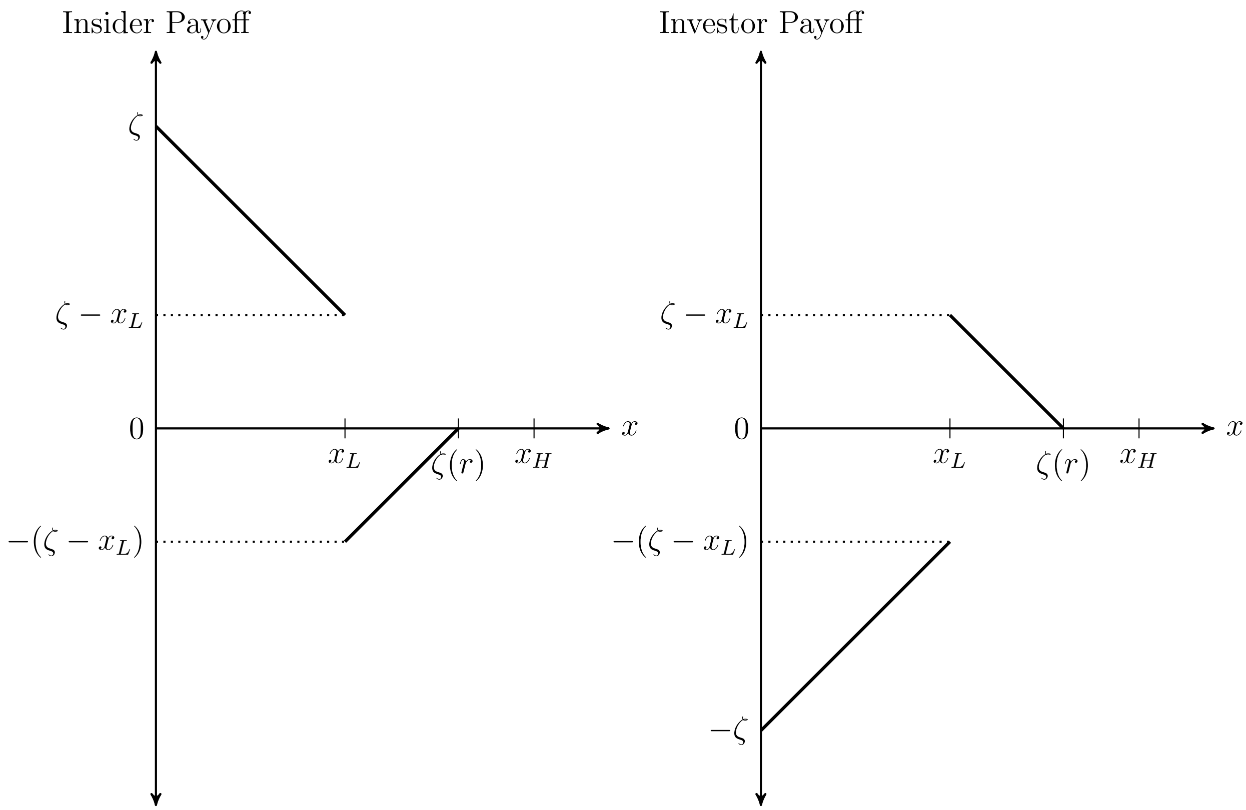

Figure 3: Mechanism Payoffs

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: 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:

$$C_0(r) \equiv \frac{q\delta[1-r]\left[\mu_J - \mu_H\right]}{\Omega(r)}. \tag{A.3}$$

Restriction 4: The personal asset liquidation cost is not too high:
We assume that the following sufficiency condition holds:

$$\frac{1-r_b}{\phi\left(r_b\right)} > l^{-1}\left[C_2\left(r_b\right)\right]^{-1}. \tag{A.4}$$

Appendix B: Proofs

Proof of Lemma 1: Clear from the text. ■

Proof of Lemma 2: Suppose counterfactually 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 1: 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:

$$f_b\Omega_b = [1+\omega]R - \theta l\Lambda, \tag{A.5}$$

where

$$\Omega_b = q\left[\overline{G} + \delta r_b A\right] + [1-q]R. \tag{A.6}$$

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

$$f_a\Omega_a = [1+\omega]R, \tag{A.7}$$

$$\Omega_a = q\left[\overline{G} + \delta r_a A\right] + [1-q]R. \tag{A.8}$$

The incentive compatibility (IC) constraint is:

$$[1-f_a]\,\Omega_a + \Lambda \geq [1-f_b]\,\Omega_a + \Lambda[1-\theta]. \tag{A.9}$$

Since this constraint is binding in equilibrium, we can solve (A.9) as an equality and obtain:

$$\theta = \frac{\Omega_a\,[f_a-f_b]}{\Lambda}. \tag{A.10}$$

Substituting in (A.10) from (A.5) and (A.6) and simplifying:

$$\theta = \frac{[1+\omega]R}{\Lambda}\left\{\frac{1-[\Omega_a/\Omega_b]}{1-l\,[\Omega_a/\Omega_b]}\right\}. \tag{A.11}$$

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

$$[1-f(\overline{r})]\,\Omega(r). \tag{A.12}$$

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

$$\left[1-\tilde{f}(\overline{r})\right]\{\Omega(r)+q\delta r\,[\mu_J-\mu_H]\}. \tag{A.13}$$

Given (A.2), we know that $\tilde{f}(\overline{r}) > f(\overline{r})$. Thus, the condition needed to ensure that no firm wishes to raise $\triangle R$ at the pooling ownership fraction $f(\overline{r})$ is that (A.12) exceeds (A.13), where

$$\tilde{f}(\overline{r})\{\Omega(\overline{r})+q\delta\overline{r}\,[\mu_J-\mu_H]\} = [1+\omega+\triangle]R. \tag{A.14}$$

A sufficient condition for (A.12) to exceed (A.13) is that

$$A\left[\tilde{f}(\overline{r})-f(\overline{r})\right] > \left[1-\tilde{f}(\overline{r})\right][\mu_J-\mu_H], \tag{A.15}$$

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 $\varepsilon(D(\tilde{r}), r)$ 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 $\varepsilon(R[1+\omega](\overline{r}), r) = [1-f(\overline{r})]\,\Omega(r)$ and $\varepsilon(R[1+\omega+\triangle](\overline{r}), r) = \left[1-\tilde{f}(\overline{r})\right]\{\Omega(r)+\delta r\,[\mu_J-\mu_H]\}$. The rest of the proof follows that for equity. ■

Proof of Proposition 2: Suppose that to finance all of $R[1+\omega]$, the firm raises D from debt and $R[1+\omega]-D$ from equity. Let $f(D)$ be the fraction of ownership insiders sell to raise this equity. Let D_R be the firm's repayment obligation on debt at $t = 3$. Clearly, debt is risky, so

$$D_R > D, \tag{A.16}$$

where D_R is given in (3). Now let $\varphi_L(D_R, [1+\omega]R)$ and $\varphi_H(D_R, [1+\omega]R)$ be the incomes sheltered from taxes due to debt when $x \sim L$ and $x \sim H$ respectively. Here

$$\varphi_L \equiv \varphi_L(D_R, [1+\omega]R) = \begin{cases} 0 & \text{if } x \leq [1+\omega]R \\ x - [1+\omega]R & \text{if } [1+\omega]R < x \leq D_R + [1+\omega]R \\ D_R & \text{if } x > D_R + [1+\omega]R \end{cases} \tag{A.17}$$

$$\varphi_H \equiv \varphi_H(D_R, [1+\omega]R) = \begin{cases} x - [1+\omega]R & \text{if } x \leq D_R + [1+\omega]R \\ D_R & \text{if } x > D_R + [1+\omega]R \end{cases} \tag{A.18}$$

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:

$$\Gamma_D = \tau q \left\{ \delta\varphi_H + [1-\delta]\varphi_L \right\}. \tag{A.19}$$

It is clear that $\Gamma_D > 0$. Let Γ^{max} be the maximum value of the debt tax shield, i.e., that which obtains when $D = [1+\omega]R$. Assume that the value loss from risk shifting is large relative to Γ_D, i.e.,

$$R - \mu_M > \Gamma^{max}. \tag{A.20}$$

This means, that for *any* capital structure, 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

$$[1 - f(D^*)]\,[R - D_R^*] = [1 - f(D^*)]\,\kappa \int_{D_R^*}^{\infty} x\,dM, \tag{A.21}$$

where D^* is the amount of debt raised that leads to a repayment obligation of D_R^*.

To maximize the value of the debt tax shield, the firm will wish to raise D^* in debt. From (A.19), the debt tax shield value will be Γ_{D^*}. Note that $\partial \Gamma_{D^*}/\partial \tau > 0$. The transaction cost of raising D^* is $T_D(D^*)$. Thus, $\exists\, \hat{\tau}$ such that

$$\begin{cases} \Gamma_{D^*} \leq T_D(D^*) \;\forall\, \tau \leq \hat{\tau} \\ \Gamma_{D^*} > T_D(D^*) \;\forall\, \tau > \hat{\tau} \end{cases}. \tag{A.22}$$

Clearly, if $\tau \leq \hat{\tau}$, the firm will not use debt and if $\Gamma_{D^*} > T_D(D^*)$, it will use D^* in debt. ■

Proof of Lemma 3: From the IC constraint (23), we obtain

$$\hat{\varphi} = \frac{\left[\hat{f}(r_a) - \hat{f}(r_b)\right]\hat{\Omega}(r_a, \triangle) + \delta q\,[1 - r_a]\,\mu_H\left[l^{-1} - 1\right]}{q\delta\,[1 - r_a]\, l^{-1}} \tag{A.23}$$

Substituting for $\hat{f}(r_b)$ from the pricing constraint (21) into (A.23) 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:

$$U_b = \left[1 - \overline{f}(r_b)\right]\hat{\Omega}(r_b, \triangle) + V_H - q\delta\,[1 - r_b]\left\{l^{-1}\left[\overline{\varphi}_I - \mu_H\right] + \mu_H\right\} \tag{A.24}$$

Substituting for $\overline{f}(r_b)$ from (29) and simplifying, we can write (A.24) as:

$$U_b = \hat{\Omega}(r_b, \triangle) - [1 + \omega + \triangle]R + V_L + \kappa V_L\left[l^{-1} - 1\right] - q\delta\,[1 - r_b]\,\overline{\varphi}\left[l^{-1} - 1\right] \tag{A.25}$$

Now, from (33) we see that:

$$\frac{\partial \overline{\varphi}(r_b)}{\partial m} = \frac{-\kappa V_L}{U_1 q\delta\,[1 - r_b]} < 0. \tag{A.26}$$

Furthermore,

$$\frac{\partial U_b}{\partial m} = -q\delta\,[1 - r_b]\left[l^{-1} - 1\right][\partial \overline{\varphi}/\partial m] > 0. \tag{A.27}$$

Thus, intermediation improves welfare.

Next, after some simplification:

$$\frac{\partial U_b}{\partial k} = V_L \left\{ \left[l^{-1} - 1\right] + \frac{\hat{a}_b}{U_1 q \delta \left[1 - r_a\right] l^{-1}} - \frac{\left[l^{-1} - 1\right]\left[1 - m\right]}{U_1} \right\} > 0 \tag{A.28}$$

for m large enough. ■

Proof of Lemma 4: 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

$$\left[1 - f_2\right] \Omega\left(r_1\right) \quad > \quad \left[1 - f_1\right] \Omega\left(r_1\right), \tag{A.29}$$

which follows since $f_1 > f_2$. Note that $f_1 > f_2$ follows from (41) and the fact that $\Omega(r)$ defined in (37) is strictly increasing in r and the right-hand side of (A.29) is a constant. Thus, the r_1 firm will misreport its type as r_2. ■

Proof of Lemma 5: Substituting from (41) into (39), we can write:

$$\begin{aligned} U(r) &= \left[\Omega(r, \triangle) - \left[1 + \omega + \triangle\right] + P_0 - P_0 l^{-1}\right] \pi(r) \\ &= \pi(r) \left[\Omega(r, \triangle) - \left[1 + \omega + \triangle\right] R - \left[l^{-1} - 1\right] P_0(r)\right]. \end{aligned} \tag{A.30}$$

We will first show that (40) 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 (40) we have that $U(r \mid r) \geq U\left(\tilde{r} \mid r\right)$, so:

$$\begin{aligned} & \pi(r) \left[\Omega(r, \triangle) - \left[1 + \omega + \triangle\right] R - \left[l^{-1} - 1\right] P_0(r)\right] \\ \geq \quad & \pi(\tilde{r}) \left[\left[1 - \tilde{f}\right] \Omega\left(r, \triangle\right) - P_0(\tilde{r} \mid r) l^{-1} + P_I(\tilde{r}) + V_L\right]. \end{aligned} \tag{A.31}$$

From ((44)) we have

$$P_0(\tilde{r} \mid r) = P_0(\tilde{r}) + \frac{q\delta\left[\tilde{r} - r\right]\left[\tilde{\zeta} - x_L\right]^2}{2\left[x_H - x_L\right]}. \tag{A.32}$$

Substituting (A.32) in (A.31) yields:

$$\begin{aligned}
&\pi(r)\left[\Omega\left(r, \triangle\right) - \left[1 + \omega + \triangle\right] R - \left[l^{-1} - 1\right] P_0(r)\right] \\
\geq &\pi(\tilde{r})\left[\left[1 - \tilde{f}\right]\hat{\Omega}\left(\tilde{r}, \triangle\right) - P_0(\tilde{r})l^{-1} - \frac{q\delta l^{-1}\left[\tilde{r} - r\right]\left[\tilde{\zeta} - x_L\right]^2}{2\left[x_H - x_L\right]} + P_I\left(\tilde{r}\right) + V_L + \left[1 - \tilde{f}\right]\hat{\Omega}\left(r, \triangle\right) - \left[1 - \tilde{f}\right]\hat{\Omega}\left(\tilde{r}, \triangle\right)\right] \\
= &U\left(\tilde{r}\right) + \pi\left(\tilde{r}\right)\left\{\frac{q\delta l^{-1}\left[r - \tilde{r}\right]\left[\tilde{\zeta} - x_L\right]^2}{2\left[x_H - x_L\right]} + \left[1 - \tilde{f}\right]\left[\hat{\Omega}\left(r, \triangle\right) - \hat{\Omega}\left(\tilde{r}, \triangle\right)\right]\right\}.
\end{aligned} \tag{A.33}$$

Now using (37) we see that

$$\hat{\Omega}\left(r, \triangle\right) - \hat{\Omega}\left(\tilde{r}, \triangle\right) = q\delta\left[\mu_J + A\right]\left[r - \tilde{r}\right]. \tag{A.34}$$

Define

$$N\left(\tilde{r}\right) \equiv \pi\left(\tilde{r}\right)\left\{\frac{q\delta l^{-1}\left[\tilde{\zeta} - x_L\right]^2}{2\left[x_H - x_L\right]} + \left[1 - \tilde{f}\right]q\delta\left[\mu_J + A\right]\right\}. \tag{A.35}$$

Substituting (A.35) in (A.33) gives us:

$$U(r) - U\left(\tilde{r}\right) \geq \left[r - \tilde{r}\right]N\left(\tilde{r}\right), \tag{A.36}$$

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

$$U\left(\tilde{r}\right) - U(r) \geq \left[\tilde{r} - r\right]N(r), \tag{A.37}$$

which implies

$$U(r) - U\left(\tilde{r}\right) \leq \left[r - \tilde{r}\right]N(r). \tag{A.38}$$

Combining (A.36) and (A.38) yields:

$$[r-\tilde{r}]\,N(\tilde{r}) \leq U(r) - U(\tilde{r}) \leq [r-\tilde{r}]\,N(r). \tag{A.39}$$

Inspection of (A.39) 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:

$$\lim_{\tilde{r}\to r} \frac{U(r) - U(\tilde{r})}{\tilde{r} - r} = U'(r) = N(r) > 0 \text{ almost everywhere.} \tag{A.40}$$

Since $N(r)$ is non-decreasing, it follows that $U'' \geq 0$ almost everywhere. Thus we have shown that (40) implies parts 1 and 2 of the Lemma.

Next, we will show that parts 1 and 2 of the lemma imply (40). Note that

$$\begin{aligned} U(r \mid r) - U(\tilde{r} \mid r) &= U(r \mid r) - U(\tilde{r} \mid r) + [r-\tilde{r}]\,N(\tilde{r}) \\ &= \int_{\tilde{r}}^{r} U'(t \mid t)dt - [r-\tilde{r}]\,U'(r \mid \tilde{r}) \\ &\geq 0, \end{aligned} \tag{A.41}$$

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

Proof of Lemma 6: 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 5), 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 7: 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:

$$\int_{r_a}^{r} U'(\tilde{r} \mid \tilde{r})\, d\tilde{r} = \int_{r_a}^{r} N(\tilde{r})\, d\tilde{r}, \tag{A.42}$$

which means

$$\begin{aligned} U(r) - U(r_a) &= \int_{r_a}^{r} N(\tilde{r})\, d\tilde{r} \\ \Longrightarrow U(r) &= U(r_a) + \int_{r_a}^{r} N(\tilde{r})\, d\tilde{r}. \end{aligned} \tag{A.43}$$

Taking the expectation of (A.43) yields:

$$\begin{aligned} \int_{r_a}^{r_b} U(r) z(r) dr &= U(r_a) + \int_{r_a}^{r_b} \left[\int_{r_a}^{r} N(t) dt \right] z(r) dr \\ &= U(r_a) + \int_{r_a}^{r_b} N(t) \left[\int_{t}^{r_b} z(r) dr \right] dt \\ &= U(r_a) + \int_{r_a}^{r_b} \phi(r) N(r) z(r) dr, \end{aligned} \tag{A.44}$$

where $\phi(r) \equiv \frac{[1-Z(r)]}{z(r)}$. Now we know from (39) that

$$\pi(r) \left[\hat{\Omega}(r, \triangle) + P_I(r) + V_L - P_0(r) l^{-1} \right] = U(r) + \pi(r) f \hat{\Omega}(r, \triangle). \tag{A.45}$$

Substituting in (A.45) for $f\Omega$ from (41) gives us:

$$\pi(r) \left[\hat{\Omega}(r) + P_I(r) + V_L - P_0(r) l^{-1} \right] = U(r) + \pi(r) \left\{ [1 + \omega + \triangle] R - P_0(r) - V_H(r) + P_I(r) \right\}. \tag{A.46}$$

Substituting (A.46) into (36) yields the objective function:

$$\int_{r_a}^{r_b} \left\{ U(r) + \pi(r) \left[[1 + \omega + \triangle] R - \Omega^* - P_0(r) + P_I(r) + V_L \right] \right\} z(r) dr. \tag{A.47}$$

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.44) in

(A.47) above to get

$$\overline{u}_a + \int_{r_a}^{r_b} \{\phi(r)N(r) + \pi(r)\left[[1+\omega+\triangle]\, R - \Omega^* - P_0(r) + P_I(r) + V_L\right]\} \, z(r)dr. \tag{A.48}$$

Now use (A.35) and write

$$N(r) = \pi(r) \left\{ \frac{q\delta l^{-1}\left[\zeta - x_L\right]^2}{2\left[x_H - x_L\right]} + [1-f]\, q\delta \left[\mu_J + A\right] \right\}, \tag{A.49}$$

so that, using (41) and (47), the intermediary's objective function (A.48) can be written as:

$$\begin{aligned} &\overline{u}_a + \int_{r_a}^{r_b} \pi(r)\phi q\delta \left\{ \frac{l^{-1}\left[\zeta - x_L\right]^2}{2\left[x_H - x_L\right]} + \left[\mu_J + A\right] \left[1 - C_1(r) + \frac{P(r)}{\Omega(r)}\right] \right\} z(r)\, dr \\ &+ \int_{r_a}^{r_b} \pi(r) \left\{[1+\omega+\triangle]\, R - P(r) + V_L - \Omega^*\right\} z(r)\, dr. \end{aligned} \tag{A.50}$$

where $P(r)$ is defined in (48). This completes the proof since maximizing (A.50) is equivalent to maximizing (A.50) 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.50) is the one that involves maximizing the integral pointwise. Thus, the first-order condition for ζ is:

$$\begin{aligned} &l^{-1}\phi(r)q\delta \left[\zeta - x_L\right]\left[x_H - x_L\right]^{-1} \\ &-C_2(r) \left\{ q\delta[1-r]\left[\zeta - x_L\right]\left[x_H - x_L\right]^{-1} - q[1-\delta] - [1-q] \right\} = 0. \end{aligned} \tag{A.51}$$

The second-order condition is:

$$l^{-1}\phi(r)q\delta \left[x_H - x_L\right]^{-1} - C_2(r)q\delta[1-r]\left[x_H - x_L\right]^{-1} < 0, \tag{A.52}$$

which holds given (A.4).

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

$$\zeta(r) = x_L + \frac{[x_H - x_L]\{q[1-\delta] + [1-q]\}}{q\delta\{[1-r] - [\phi(r)/C_2(r)]\, l^{-1}\}}, \tag{A.53}$$

which is (49). 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.50) also reveals that the mechanism designer will set $\pi = 1$ whenever the term multiplying $\pi(r)$ in (A.50) 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. ■