Information-Concealing Credit Architecture *

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Abstract

When the value of a pledgeable asset (or project) is uncertain, investors are tempted to examine it. The information cost is ultimately borne by the asset owner, reducing her financing capacity. A pecking order emerges. Debt generates a greater financing capacity than equity: unlike equity investors who own the asset directly, creditors own the asset only if the borrower defaults and, therefore, have weaker incentives to acquire information. The probabilistic asset ownership can be further diluted by introducing intermediaries between the borrower and the creditor, leading to a new theory of financial intermediation and credit chains. We demonstrate that the optimal financial architecture involves systematically sequencing multiple intermediaries with heterogeneous information costs and asset correlations, rationalizing the seemingly excessive complexity of intermediated credit flows.

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1 Introduction

The financial system operates through a highly intricate network of intermediated funding and collateral flows.[1] The complexity of credit intermediation has been widely criticized for its opacity, which induces contagion by obscuring systemic vulnerabilities, creates significant regulatory challenges, and complicates crisis management efforts.[2] While this seemingly excessive complexity and opacity are often framed as either a byproduct of risk distribution or an intentional attempt to obscure excessive risk-taking, we argue that complex credit flows involving a network of intermediaries maximize credit capacity for the real economy. This result constitutes a cautionary tale for regulators that aim to enhance transparency by reducing the complexity of intermediated fund flows, as they must also consider the unintended consequences of reducing financing capacity.

How can an asset or a project be used to maximize credit capacity? If there is uncertainty about its exact value but such uncertainty is symmetric between the borrower and lender, then the maximum capacity is achieved "in the dark:" credit capacity based on the expected asset value (an *information-insensitive loan*) is higher than the average of credit capacities under the realized asset values (an *information-sensitive loan*). This is generally the case once the cost of acquiring information about the realized values is taken into account. To sustain information-insensitive loans, however, lenders must be willing to lend "in the dark" against an asset's expected value without the incentive to examine it before lending takes place so as to exploit the superior information.

We show a lender is willing to lend in the dark, "no questions asked," when the asset or project has certain properties, such as low uncertainty in its value or high information acquisition cost, which points towards the role of designing the asset itself that has been analyzed in the existing literature.[3] The lender is also willing to lend in the dark when the likelihood of ending up in possession of the asset is low. This last dimension is the one we highlight in this paper.

[1]This structure has been widely documented and explored by Aguiar et al. (2016).

[2]FRBNY (2020) provides a recent policy discussion on systemic vulnerability. Initiatives such as the G20-led push for central clearing and EU's "Simple, Transparent, Standardized" securitization framework reflect a consensus on curbing complexity (e.g., G20 (2018); EU (2022)). Living wills and reforms, such as the UK's ring-fencing regime, illustrate attempts to facilitate crisis management under complex fund flows (e.g., Dallas Fed (2012); PRA (2022)).

[3]See a discussion of how the design of collateral assets, such as pooling or tranching assets, can discourage costly information acquisition in Chapter 2 of Gorton and Ordonez (2023).

We highlight such incentives by proposing a setting in which debt and equity only differ in the likelihood that the funding provider ends up owning the borrower's asset. This asset can correspond to capital that sustains a firm's production, a financial asset, real estate, or projects with verifiable and contractable cash flows. Obtaining funds by issuing equity is akin to selling the asset: the investor *always* ends up owning the asset. Instead, issuing debt implies the lender obtains the asset only if the borrower defaults; the lender *does not always* end up owning it. In summary, different from equity, debt carries a *probabilistic asset ownership*.

This difference in the likelihood of owning the asset implies that equity introduces stronger incentives to acquire information than debt. As a result, a pecking order emerges. Financing capacity is constrained by incentive compatibility (IC) for information-insensitive contracts, because the investor's incentive to acquire information increases with funding. The incentives to acquire information are weaker with debt, relaxing the IC constraints and enlarging financing capacity.

There are situations, however, in which Modigliani-Miller applies, and debt and equity are identical. At one extreme, if the cost of information is so high that the investor would not acquire information, financing capacity would be the same with *information-insensitive* debt and equity. At the other extreme, if the cost of information is so low that the borrower prefers to compensate for the investor's cost of information than to discourage information production, financing capacity would be the same with *information-sensitive* debt and equity. These extreme cases are not our focus. We characterize the parameter conditions under which *information-insensitive* debt dominates equity and information-sensitive securities and thus maximizes the financing capacity by reducing the funding provider's incentives to produce information and saving the information cost.

Our notion of a pecking order differs from that of Myers and Majluf (1984). They show a hierarchical financing strategy given the degree of information asymmetry between the firm and investors: managers know more about their company's prospects than investors. In their work, the extent of information asymmetry is fixed, and the choice of which security to issue is based on the degree of adverse selection. We depart from the presumption of asymmetric information and show that a pecking order emerges to prevent endogenous information production.

After establishing the optimality of information-insensitive debt, we show that designing an intermediation chain can increase credit by further diluting probabilistic asset ownership. Our analysis speaks directly to the complexity of credit flows intermediated by various financial institutions and demonstrates how such complexity enlarges the financing capacity for the end borrower. Consider an intermediary that extends a loan to *an end borrower* and borrows from *an end lender* pledging the loan as collateral. Only when both the end borrower and intermediary default do the end lender take possession of the asset. If we assume, realistically, that the intermediary's insolvency is not perfectly correlated with that of the end borrower (for example, due to the intermediary holding other assets), the probability of both the end borrower and intermediary going bankrupt is lower than the borrower alone going bankrupt. As a result, the end lender's probability of owning the asset declines in the presence of an intermediary. But how about the intermediary's incentives to acquire information? These are weaker than that of the lender in the absence of intermediation: for the intermediary to own the end borrower's asset, two events must happen—the borrower defaults and the intermediary itself survives—which has a lower probability than the single event of the borrower's default. Therefore, under intermediated financing, both the end lender and the intermediary have weaker incentives to produce information than the lender under direct financing.

Here the intermediary does just that. It intermediates. It does not introduce commitment or expertise as in other theories of intermediation. Why is its participation beneficial? In essence, the intermediation chain dilutes the possibility that any given party ends up with the asset, discouraging any party's examination of the asset. The presence of an intermediary whose portfolio is not perfectly correlated with the borrower's asset—that is, it can survive in situations in which the borrower cannot—distributes the likelihood of the borrower's default and that of taking possession of the borrower's asset among two parties (the intermediate lender, i.e., the intermediary, and the end lender who ultimately provides funds), reducing both parties' incentives to acquire information.

Does this logic of distributing the asset possession probability among lenders on the credit chain imply that the chain should include as many intermediaries as possible? Should the current chain not achieve the maximum borrowing capacity for the end borrower, i.e., the expected value of her backing asset, we show that extending the chain to enlarge credit capacity requires inserting an additional intermediary into the "*chain's bottleneck*": the link has the smallest funding capacity as the lender in the link has the strongest incentive to produce information among all lenders on the chain. Inserting an intermediary into the bottleneck link does not change the probability of asset possession for the preceding intermediaries ("upstream") but unequivocally reduces the probability of asset possession for all the subsequent lenders ("downstream"). We show that, as long as the new intermediary is less tempted to produce information than the bottleneck's lender (i.e., it has a higher information cost or a lower survival probability conditional on receiving the asset), its addition to the chain enlarges its capacity to channel funding.

When the chain is being extended and multiple intermediaries satisfy the condition above, which intermediary should be included? This problem is challenging because inserting an intermediary affects whether and which intermediaries will be included in the subsequent steps of chain extension. A local optimum may not be the global optimum. First, we show that an optimal chain should equalize the incentives to acquire information across lenders in all links, so to avoid bottlenecks. The intuition is similar to that of maximizing the Leontief production function. In a setting in which intermediaries differ in costs of information production and survival probabilities conditional on receiving the end borrower's asset (i.e., the two forces that drive the incentives to produce information), intermediaries with low information costs should be placed later on the chain so that their probability of asset possession is low, while lenders with high information costs can be placed earlier, because even though this makes them more like to receive the asset (as they face more directly the end borrower's default), their high information cost discourages information production. In a simpler setting where intermediaries have the same information costs, those most correlated with the end borrower are placed earlier in the chain. Importantly, we demonstrate that the optimal chain emerges endogenously in a laissez-faire environment, reflecting exactly this principle.

Our model suggests that the formation of a long credit chain is meaningful only when intermediaries hold heterogeneous and imperfectly correlated assets. For the intuition, consider instead a scenario of homogeneous and independent assets—that is, conditional on the end borrower's default, intermediaries have independent and identical survival probabilities. The optimal chain only needs one intermediary: while inserting more intermediaries weakens the incentive to produce information for the downstream lenders, but the bottleneck remains between the end borrower and the first intermediary, whose probability of receiving the asset (i.e., the end borrower's default) does not change and the conditional survival probability is the same under the i.i.d. assumption. In contrast, when intermediaries hold heterogeneous and correlated assets, there is room for the chain to enlarge funding capacity by involving many intermediaries and properly sequencing them.

While our main analysis takes as given the risk profile of the end borrower's asset and assets of the intermediaries, it has unique implications for endogenous asset choices. We demonstrate that an equilibrium exists in which an intermediary may forgo productive investments and opt for safe assets ("bonds") for two reasons. First, when the intermediary raises funds from a lender by pledging bonds as collateral, those safe bonds do not induce information production by the lender thereby enlarging the intermediary's fund-raising capacity. Second, when the intermediary lends to a borrower, holding bonds allows it to stay uninformed about the borrower's asset, because, due to the lack of expertise in examining risky assets, the intermediary faces a high information cost.

Relation with the literature. At the core of our model is a simple observation: debt carries a probabilistic ownership of the backing asset. Since the funding provider's cost of examining the asset is ultimately borne by the borrower, the borrower's financing capacity is maximized under information-insensitive contracts, and debt dominates equity (full asset ownership) because it induces weaker incentives for the funding provider to acquire information. Our pecking-order theory of capital structure differs from Myers and Majluf (1984). Importantly, it generates new and unique implications on financial intermediation: financing capacity is enlarged when the probability of owning the backing asset is diluted by inserting intermediaries between the borrower and the funding provider. We provide a new view of financial intermediation: it does not generate information but conceals it with the help of opaque funding networks. The only role of intermediaries is to be there and intermediate. Intermediaries do not have any expertise in our model.

Our work is related to Diamond (1984) who shows that by diversifying portfolios, banks can dilute the need to monitor upon default and improve credit provision. In our model, the "diversification" happens along credit chains. It is not about diversifying across different assets but instead, given an asset, credit chains distribute (probabilistic) asset ownership across lenders along the chains, reducing their incentive to acquire costly information and thus enlarging credit capacity.

Our model complements studies that emphasize designing opaque assets and institutions to provide liquidity and facilitate credit. In Dang et al. (2017), for instance, banks improve on credit provision by making their assets as opaque as possible. We show that instead of making intermediaries opaque, forming intermediary networks also enhances opaqueness and enlarges credit capacity. The seemingly spurious interconnectedness is created to conceal information.

Our theory also offers a new rationale for understanding intermediaries' asset correlation. In Farhi and Tirole (2012), financial intermediaries correlate their portfolios to increase the probabilities of government bailout in case of default, as those defaults would happen in tandem. In our case, asset correlation lays the foundation for credit chains to emerge. A chain increases its capacity to channel funds by properly sequencing correlated and yet heterogeneous intermediaries. Highly correlated intermediaries are positioned upstream (closer to the end borrower), because even though their probabilities of receiving the end borrower's asset are high, their probabilities of survival conditional on the end borrower's and preceding intermediaries' insolvency are low. The less correlated intermediaries are positioned downstream. Their low probability of receiving the asset counterbalances high conditional survival probabilities in deterring information production.

Therefore, beyond a theory of capital structure and financial intermediation, our model highlights two new sources of ex-ante heterogeneity among intermediaries—information cost and conditional survival probabilities—that lead to endogenous network formation. Note that the relevant conditioning event for intermediaries' survival is the insolvency of the end borrower and all preceding intermediaries on credit chains, which is chain-specific and thus differs from other measures of intermediaries' financial health in the existing literature.[4] Moreover, our focus is on the formation of intermediation networks (chains) rather than how networks propagate shocks ex-post.[5]

Our paper emphasizes that intermediation chains weaken incentives to obtain informational advantage and create information asymmetry. Glode and Opp (2016) and Glode, Opp, and Zhang (2019) take information asymmetry as given and study how intermediation chains mitigate the associated inefficiency. Furthermore, in their papers, intermediaries (dealers) facilitate asset trading

[4] In the existing literature, bank heterogeneity in liquidity needs or investment opportunities leads to the formation of interbank credit or insurance networks (e.g., Allen and Gale, 2000; Brusco and Castiglionesi, 2007; Afonso and Lagos, 2015; Babus, 2016; Corbae and Gofman, 2019; Craig and Ma, 2022; Farboodi, 2023).

[5] Please refer to Jackson and Pernoud (2021) for a literature review on shock propagation.

in spot markets, while, in our model, intermediaries sign bilateral (debt) contracts.[6]

A recent body of literature examines credit chains. Our model differs in that intermediaries neither possess expertise nor have unique access to markets or trading relationships. Intermediaries are just there to dilute the probabilistic asset ownership along credit chains. Moreover, we do not assume a particular financing contract (debt) to be optimal; based on the fact that debt carries probabilistic asset ownership, we derive a complete theory of debt optimality, credit intermediation, and credit chains. Among the related papers on credit chains, Maggio and Tahbaz-Salehi (2014) study how the distribution of collateral along predetermined credit chains affects funding capacity and systemic stability. In Donaldson and Micheler (2018), credit chains arise to mitigate liquidation losses when banks rely on non-resaleable debt (e.g., repo). In He and Li (2022), the intermediation chain emerges to address maturity mismatch and costly liquidation associated with the failure to roll over debts. Donaldson, Piacentino, and Yu (2022) study financial stability implications of chains of long-term debts that allow borrowers to dilute existing creditors' claims by issuing new debts. Glode and Opp (2023) study debt renegotiation on a predetermined credit chain.[7]

One form of issuing debt backed by the borrower's asset is a repurchase agreement (repo). Note that repo requires spot exchange of both cash and collateral, while in our model, only cash exchange (from the lender to the borrower) is necessary. Issuing equity corresponds to raising funds by selling the asset. Under this interpretation, our model speaks to the superiority of repo over asset sale as a way of raising funds. Our explanation differs from Parlatore (2019), who argues that firms would rather pledge financial assets as collateral than sell them when the return on firms' investment is not observed, the asset is not liquid, or the investment opportunities are persistent. Our theory also differs from Monnet and Narajabad (2012) who emphasize bilateral trading frictions. In our model, all of these frictions are absent. The key to understanding why debt dominates equity—and, relatedly, why repo dominates asset sales as a means of raising funds—

[6]Chains of spot asset exchanges also emerge in models of over-the-counter (OTC) markets, often in the absence of informational frictions (e.g., Viswanathan and Wang (2004); Gofman (2014); Atkeson et al. (2015); Chang and Zhang (2015); Wang (2016); Babus and Kondor (2018); Hugonnier et al. (2019); Sambalaibat (2019); Hendershott et al. (2020); Colliard and Demange (2021); Shen et al. (2021)).

[7]Beyond the literature on credit chains, recent studies also analyze the chain of delegated (equity) asset management (e.g., Dasgupta and Maug (2021); Zhong (2023)). Their focus is on asset managers' differences in skills.

lies in the distinction between probabilistic asset ownership under debt and full asset ownership under equity. Probabilistic asset ownership weakens information-production incentives.

In our model, credit chains that emerge in equilibrium reflect repo and collateral rehypothecation, a common phenomenon, particularly in the lead-up to the global financial crisis (GFC) (e.g., Fuhrer, Guggenheim, and Schumacher (2016); Gorton, Laarits, and Muir (2022)). The driving force of weakening information-production incentives through the dilution of asset ownership is distinct from those in the existing studies. Several papers emphasize cash lenders' default (failure to return collateral) (e.g., Eren (2014); Infante (2019); Kahn and Park (2019); Infante and Vardoulakis (2020); Maurin (2022)). Rehypothecation arises from collateral scarcity when agents face liquidity constraints (e.g., Andolfatto, Martin, and Zhang (2017); Jank, Moench, and Schneider (2022); Infante and Saravay (2024)) or to relax leverage and short-sale constraints (e.g., Bottazzi, Luque, and Páscoa (2012), Gottardi, Maurin, and Monnet (2019), Brumm et al. (2023)).

Finally, our work contributes to the ongoing discussion about the desirability of complex financial systems. While most of this literature has highlighted the negative consequences of such complexity, such as Stiglitz (1999) and Caballero and Simsek (2013), we instead emphasize the rationale for such complexity to improve credit provision in the economy.

The next section introduces a model of capital structure where costly information acquisition and the probabilistic asset ownership of debt give rise to a pecking order theory. Section 3 shows that intermediation dilutes the probabilistic asset ownership and thereby enlarges credit capacity. Section 4 characterizes optimal intermediation chains with multiple heterogeneous intermediaries. In Section 5, we analyze firms' asset choices. We make the final remarks in the last section.

2 Optimal Financing: A Pecking Order

We analyze a general problem of financing liquidity needs when the value of pledgeable assets is ex-ante uncertain, both to those who demand and those who supply liquidity. In this section, we focus on a firm either obtaining funds from a deep-pocket investor (if funds are channeled through an equity contract) or from an end lender (if funds are channeled under a debt contract).

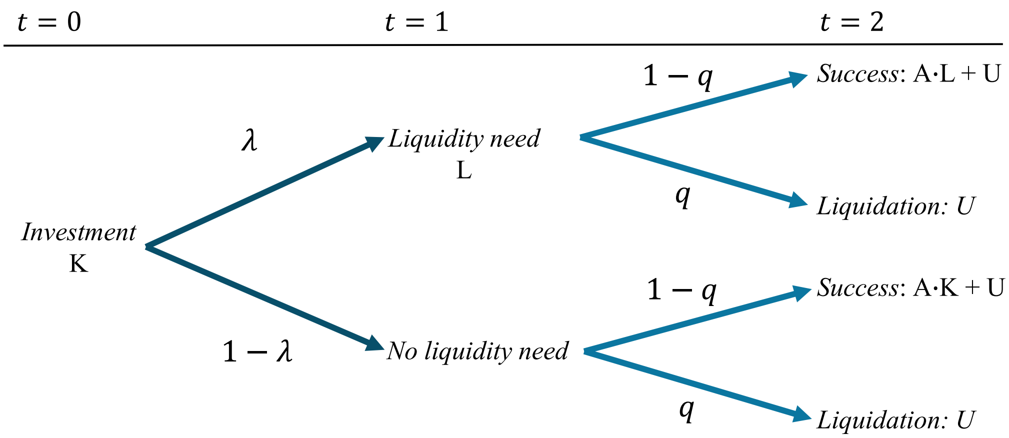

Figure 1: **Project Timeline.**

In the next section, we allow for a richer environment with multiple firms that act as intermediary lenders, forming a credit chain between the borrower and the end lender.

2.1 The Setup

The economy has three dates, $t = 0$, 1, and 2. There are two agents: a firm and a deep-pocket investor. They are risk-neutral with a zero discount rate. At $t = 0$, the firm has endowment K, which is fully invested in a project. The project involves capital and real estate that are needed for the operation and represent pledgeable assets with liquidation value U at $t = 2$. We assume U is uncertain at $t = 0$. The project also generates nonpledgeable, stochastic profits: with probability q, the project does not generate any profit, and with probability $(1 - q)$, it generates $A > 1$ per unit of investment. We assume, however, that at $t = 1$ the firm may be hit by a liquidity shock with probability λ. In this case, the firm needs to raise new funds to maintain operations, possibly at a reduced scale. In particular, if the firm raises $L \in [0, K]$ it can operate at a scale that is L/K of the original size, and obtain profits AL if successful. This timeline is illustrated in Figure 1.

We assume that the pledgeable value, U, is equal to G with probability p and B ($< G$) with probability $1 - p$. Let $\bar{U}$ denote the expected pledgeable value of the project

$$\bar{U} = pG + (1 - p)B. \tag{1}$$

Without the uncertainty in U, the model is rather trivial: the firm would raise up to U in case of a liquidity need. We introduce the uncertainty in U so that we can meaningfully discuss information acquisition and its implications on whether to obtain funds using equity or debt, and the project's financing capacity. We will show how such uncertainty determines optimal financing contracts and financial architecture (the nexus of contractual relationships in the presence of multiple firms or financial intermediaries).

The information environment is specified as follows. At $t = 1$ when the liquidity shock hits, the firm does not know whether the liquidation value is G or B. At $t = 1$, the investor does not know the liquidation value either but can learn about it by paying a cost, C.[8] Information acquisition cannot be forced or prohibited. Once she knows the liquidation value, the information is revealed to the firm as well. At $t = 2$, the firm knows whether the project succeeds, but the investor does not and cannot learn about it. Note that in the standard costly verification model (Townsend (1979)), the lender can learn about the project's success or failure A at a cost, but in contrast, the investor in our model may learn about the liquidation value U.

Let's highlight again the main assumptions that allow us to focus on the core mechanism around costly information acquisition. First, the firm has to invest its whole endowment to start the project at $t = 0$, so it cannot self-insure against the liquidity shock at $t = 1$. We also rule out external financing at $t = 0$ to focus solely on the problem of external financing at $t = 1$ should a liquidity shock hit. Second, the project always has a pledgeable liquidation value of U that is independent of the liquidity shock or the project's success. Third, the cash flows from a successful project—AK without being hit by the liquidity shock and AL after the liquidity shock—cannot be pledged for external financing. These assumptions guarantee that the firm's financing capacity is tied to the uncertain value of U, while its incentive to raise financing, L, in the liquidity event (to generate AL) is tied to productivity A. Such separation allows a transparent exposition of our

[8] We only endow the investor with a technology to learn about the liquidation value, not the borrower. One example of such asymmetry is the real estate market: the borrower takes out a mortgage from a bank and triggers a credit chain that involves the bank, repo market, a rehypothecation chain, and money market funds. The borrower does not know value of the real estate as well as the financial professionals on the chain. We can assume that both sides have information technologies to assess the liquidation value without fundamental changes in insights. However, only the investor's incentives motivate the formation of intermediation chains that we discuss in Sections 3 and 4, respectively.

mechanism.[9] We also make a couple of parametric assumptions to avoid unnecessary complications in the analysis, so we can focus on our proposed mechanism.

Assumption 1 *Throughout the analysis, we maintain the following set of parametric conditions:*

- $K \geq G$*: in the liquidity event, financing based on even the highest liquidation value is still insufficient to refinance the project to its original capacity.*
- A *is sufficiently high: the firm wants to maximize refinancing in the liquidity event.*

Next, we analyze the financing structure in the liquidity event at $t = 1$. In our model, equity represents the investor's *direct ownership* (shares) of U, while debt carries a *probabilistic ownership*—a lender owns U only if the firm defaults on the contractual repayment, a probability q event. We will show probabilistic ownership weakens a lender's incentive to produce costly information, so the project's financing capacity is larger under debt than equity.

2.2 Equity Financing

The firm issues equity shares of the liquidation value, U. The number of shares is normalized to one. We consider information-sensitive and information-insensitive equity. In the former case, the investor pays the cost C to learn about U. For the investor to break even, the cost of information acquisition must be compensated through a discount in the equilibrium price of equity, implying a financing capacity in expectation less than $\bar{U}$. In the latter case, equity price does not suffer from an information-cost discount, but the financing capacity is limited by an incentive-compatible (IC) condition that prevents the investor from deviating and privately acquiring information about U.

The next lemma summarizes the ex-ante financing capacity for each type of equity, and the ex-ante surplus each generates to the firm. Since we assume the investor breaks even, the firm's surplus is also the social surplus. The proof is in Appendix A.

[9] For interpretation, one may regard the liquidation value as what the investor can repossess, and through the threat of liquidation, the investor enforce the contractual payoff. Alternatively, one may view A as unobservable and unverifiable, and A can also be inalienable from the firm manager's human capital.

Lemma 1 (Equity financing capacity and ex-ante surplus)

• *Optimal information-sensitive equity contract: The firm raises funds in expectation* $\mathbb{E}(E^s) = \bar{U} - C$ *and generates expected surplus* $(1-q)A(\bar{U} - C) - \bar{U}$ *in the liquidity event.*

• *Optimal information-insensitive equity contract: The firm raises funds* $E^i = \min\left\{\bar{U}, \Gamma C\right\}$ *, where*

$$\Gamma = \frac{1}{p\left(\frac{G-\bar{U}}{\bar{U}}\right)}, \tag{2}$$

and generates expected surplus $(1-q)AE^i - E^i$ *in the liquidity event.*

When the firm sells shares to raises funds using an information-sensitive contract, the price of equity is contingent to the realization of U minus the information cost, hence in expectation the price is $\bar{U} - C$, where the discount, C, compensates the investor's information cost. The surplus has two parts. The first part, $(1-q)A(\bar{U} - C)$, is the expected profits from investing the funds raised via equity issuance, where, as previously stated, $1-q$, is the probability that productivity A materializes. The second part, $-\bar{U}$, reflects the fact that the firm pledges the full liquidation value $\bar{U}$, which covers both the investment cost, $\bar{U} - C$, and the investor's information cost, C.

In contrast, when the firm sells shares to obtains funds using an information-insensitive contract, the price of equity is not contingent on the realization of U, and the surplus in this case does not reflect the cost of information acquisition. However, for this contract to be incentive-compatible (IC)—that is, it does not induce the investor's information production—the firm may be restricted to sell only a fraction of the pledgeable value, i.e., $E^i < \bar{U}$ when $\Gamma C < \bar{U}$. Raising funds beyond the IC limit, ΓC, tempts the investor to acquire information because too much is at stake. Notice that Γ captures the properties of U related to its "information worthiness": the investor's incentive to acquire information is stronger when there is a higher probability p of discovering a good asset whose value deviates significantly from the expected value $\frac{G-\bar{U}}{\bar{U}}$. Therefore, the financing capacity is larger when Γ is higher (U is less information-worthy) and when the investor's information cost, C, is higher, as both forces discourage information production.

2.3 Debt Financing

Now we consider a debt contract that specifies the lending amount, the promised repayment, and a covenant on the percentage of liquidation value (collateral) seized by the lender in case there is no repayment. Again, we consider information-sensitive and information-insensitive debt. In the former, the lender pays the cost C to learn about U, which has to be compensated by the borrower through the contract. In the latter case, the loan is limited by an incentive-compatible (IC) condition that guarantees the lender would not deviate and acquire information privately about the collateral.

The next lemma summarizes the ex-ante credit capacity of each type of debt, and the expected social surplus each contract generates. As in the case of equity financing, the investor (lender) breaks even, so the social surplus fully goes to the firm. The proof is in Appendix B.

Lemma 2 (Credit capacity and ex-ante surplus)

- *Optimal information-sensitive debt contract: The firm raises funds $\mathbb{E}(L^s) = \bar{U} - C$ in expectation and generates an expected social surplus $(1-q)A(\bar{U}-C) - \bar{U}$ in the liquidity event.*
- *Optimal information-insensitive debt contract: The firm raises funds $L^i = \min\left\{\bar{U}, \Gamma\frac{C}{q}\right\}$ and generates an expected social surplus equal to $(1-q)AL^i - L^i$ in the liquidity event.*

Using information-sensitive debt, the firm borrows in expectation $\bar{U}$, net of the information cost C that should be compensated to the lender. The surplus is given by the profits from investing the funds raised, $\bar{U} - C$, net off the fully pledged collateral value, $\bar{U}$, that covers both the investment cost, $\bar{U}$, and the investor's information cost, C. Both the expected financing amount and surplus are equal to the values obtained under an information-sensitive equity contract (see Lemma 1).

In contrast, when the firm borrows using an information-insensitive contract, the loan is not contingent on the realization of U, and the surplus does not reflect the cost of information acquisition. However, for this contract to be incentive-compatible, the loan size cannot exceed $\Gamma\frac{C}{q}$; otherwise, with too much at the stake, the investor is tempted to produce costly information. If $\Gamma\frac{C}{q} < \bar{U}$, credit capacity is below the pledgeable value. As in the case of equity, Γ summarizes the attributes of the pledgeable value that discourage information production. Importantly, however, with a debt contract, credit capacity is high when the probability the project fails is low (i.e., q is low). This is not due to the lender's risk aversion and credit risk being priced in equilibrium. In our model, the lender is risk-neutral. The link between default probability and credit capacity emerges from the lender's information choice. When q is low, it is unlikely that the firm defaults and the lender ends up in possession of the asset, so the lender is not incentivized to examine the asset.

2.4 An Informational Theory of the Pecking Order

According to Lemma 1 and 2, information-sensitive debt and equity generate the same financing capacity and social surpluses. Therefore, under costly information acquisition, our analysis reaches a Modigliani–Miller style result—that is, debt and equity are equivalent. Next, we show that meaningful difference emerges between information-insensitive debt and equity and between information-insensitive debt and information-sensitive debt (and equity).

Comparing the financing capacities from information-insensitive equity and debt in Lemma 1 and 2, respectively, we can see that the latter allows for a greater financing capacity when $q < 1$,

$$\Gamma \frac{C}{q} > \Gamma C. \tag{3}$$

While a lender receives the asset with probability q (when the borrower defaults), an equity investor always owns it. Since producing information is more beneficial when the likelihood of owning the asset increases, equity induces a stronger incentive to produce information than debt and thus has a tighter IC constraint and a smaller financing capacity. If an information-insensitive equity contract is feasible, an information-insensitive debt contract is also feasible. The reverse is not true.

Now we compare the alternatives. When $\Gamma \frac{C}{q} > \Gamma C > \bar{U}$, both information-insensitive debt and equity are feasible and achieve the maximum credit capacity. However, in the parameter region where $\Gamma \frac{C}{q} > \bar{U} > \Gamma C$, the debt contract generates a greater surplus as it is possible to borrow the full pledgeable value $\bar{U}$ with debt but not with equity. Therefore, our model generates a new pecking order theory—debt is preferred to equity—based on costly information production. Moreover, when information-insensitive debt achieves the full financing capacity, $\bar{U}$, it dominates information-sensitive debt and equity that only deliver an expected financing capacity of $\bar{U} - C$.

Now, let's consider the case in which $\Gamma\frac{C}{q} < \bar{U}$. Here information-insensitive debt does not allow to borrow $\bar{U}$, while information-sensitive debt is costly in terms of information production. The social surplus generated by information-insensitive debt is given by $[(1-q)A-1]\Gamma\frac{C}{q}$ which is greater than the social surplus generated by information-sensitive debt (or equity), $(1-q)A(\bar{U}-C)-\bar{U}$, if and only if

$$\frac{C}{\bar{U}} > \left[\frac{(1-q)A}{(1-q)A-1} + \frac{1}{p\left(\frac{G-\bar{U}}{\bar{U}}\right)q}\right]^{-1}. \tag{4}$$

The information-insensitive debt dominates if the cost of acquiring information is sufficiently high relative to the expected pledgeable value, which is more likely to be satisfied when the project productivity, A, is high, when the liquidation value is not information-worthy, i.e., $p\left(\frac{G-\bar{U}}{\bar{U}}\right)$ is low, and importantly, when the probability of default (and the lender receiving the asset), q, is low.

The next proposition summarizes these results.

Proposition 1 (Pecking order under information choice) *Under costly information production, the optimal financing structure has the following properties:*

1) *Information-insensitive debt dominates information-insensitive equity. Incentives to acquire information with debt is weaker than that for equity when $q < 1$.*

2) *Information-sensitive debt and information-sensitive equity are equivalent.*

3) *Information-insensitive debt dominates information-sensitive debt and equity if and only if the condition (4) holds.*

Discussion: Repo vs. asset sale. Our model not only introduces a new theoretical foundation for the optimal financing structure but also explains why many firms, and in particular, financial firms pledge assets as collateral and issue secured debt (for example, through a repurchase agreement) to raise funds rather than simply sell their assets. Selling assets is equivalent to selling equity, as in both cases, the asset buyer or equity investor takes the full ownership. The incentive to produce costly information is stronger than a secured lender's incentive, because, the lender only takes probabilistic ownership, that is she only receives the asset (collateral) when the borrower defaults. Secured debt reduces the incentive of costly information production and thereby enlarges the funding capacity. Note that in our model, a repurchase agreement (repo) and secured debt are equivalent as both represent a probabilistic ownership of the collateral. In practice, repo requires the borrower to immediately hand over the collateral to the cash lender and retrieves the collateral after making the repayment, while a secured debt contract only requires the borrower to hand over the collateral ex post in default. Such distinction is not meaningful in our model.

3 Endogenous Intermediation

We extend the environment adding another firm that is ex-ante identical to the one considered in the previous section. We assume that, while the two firms' liquidity shocks are uncorrelated, their project failure can be correlated. Specifically, the *unconditional probability* of project failure is q for both firms as in the previous section. Given the failure of one firm, the *conditional probability* that the other firm fails is $\phi \in (0, 1)$. We assume that the condition (4) holds, and accordingly, we focus on information-insensitive debt as the preferred contract. Hence credit capacity is $L = L^i$.

When a firm, labeled as "F", is hit by the liquidity shock, the amount of information-insensitive debt it can issue directly to the lender is given by $\min\{\bar{U}, \Gamma C/q\}$ as in Lemma 2. F may also seek intermediated financing via a credit chain—that is, F borrows from the other firm (an intermediary), pledging U as collateral, and the intermediary repledges it to the end lender. The repledging of collateral can be *implicit* if collateral ownership is transferred only upon default at $t = 2$ (usual bank credit), or *explicit* if the collateral is an asset that can be separated from the project's operation (e.g., a financial asset) and it is transferred along the credit chain at $t = 1$ and repurchased at $t = 2$ upon debt repayment (usual repo agreement with rehypothecation).[10]

Next, we show that intermediation enlarges financing capacity. The amount of information-

[10]In fact, any form of financial intermediation can be viewed as rehypothecating claims (e.g., Rampini and Viswanathan (2019)). Our model does not distinguish explicit and implicit rehypothecation.

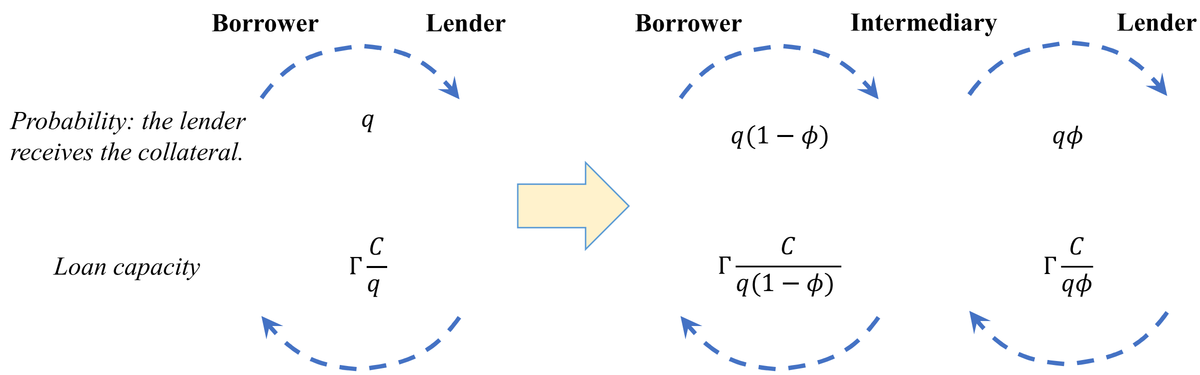

Figure 2: **From Direct Financing to Intermediated Financing.**

insensitive debt the intermediary can raise from the end lender is given by

$$L_1 = \min\left\{\bar{U},\, \Gamma\frac{C}{q\phi}\right\}, \tag{5}$$

where the subscript "1" is for the first step of fund channeling. The difference relative to the credit capacity of direct financing, $\min\{\bar{U}, \Gamma C/q\}$ in Lemma 2, is that q is replaced by $q\phi$. Conditional on F's default, which happens with probability q, the probability of the intermediary's default is ϕ. Therefore, the joint probability of both defaulting is $q\phi$. Since the end lender's incentive to acquire information depends on the probability of receiving the collateral (both firms defaulting), $q\phi$ instead of q shows up in the IC constraint for information-insensitive debt and the credit capacity.

Now consider the amount of information-insensitive debt F can raise from the intermediary:

$$L_2 = \min\left\{\bar{U},\, \Gamma\frac{C}{q(1-\phi)}\right\}, \tag{6}$$

where the subscript "2" is for the second step of fund channeling. Here q in the credit capacity of direct financing, $\min\{\bar{U}, \Gamma C/q\}$ in Lemma 2, is replaced by $q(1-\phi)$, the probability that F defaults and the intermediary does not (i.e., the probability that the intermediary ends up owning the asset). Figure 3 represents these flows and the credit capacity with and without intermediation.

Through intermediated financing, F's information-insensitive credit capacity is given by

$$L = \min\left\{\bar{U},\, L_1,\, L_2\right\} = \min\left\{\bar{U},\, \Gamma\frac{C}{q\phi},\, \Gamma\frac{C}{q(1-\phi)}\right\} = \min\left\{\bar{U},\, \Gamma\frac{C}{\widehat{q}}\right\}, \tag{7}$$

where we define a composite probability

$$\widehat{q} = \max\{q\phi,\, q(1-\phi)\}. \tag{8}$$

Under $\phi \in (0,1)$, we have $\widehat{q} < q$ and L is greater than direct financing, $\min\{\bar{U}, \Gamma C/q\}$ in Lemma 2. From $\widehat{q} = \max\{q\phi,\, q(1-\phi)\}$, it is clear that intermediated financing boosts funding capacity by diluting both the end lender's and intermediary's incentive to produce information.

The composite probability, $\widehat{q} = \max\{q\phi,\, q(1-\phi)\}$, reflects a funding *"bottleneck"*. A lower ϕ weakens the end lender's incentive to produce information as it is less likely that the intermediary will default and pass along the asset when F defaults. However, a lower ϕ strengthens the intermediary's incentive to produce information as its conditional survival probability increases. The correlation structure that balances these two forces and maximizes credit capacity is $\phi = 1/2$, i.e., when the two firms are uncorrelated—conditional on one firm's failure, the failure or success probability of the other firm is 50%. Under $\phi = 1/2$, the incentive of information production is well balanced between the end lender and intermediate lender. When we extend the network to include more than one intermediary in Section 4, we will expand on the intuition of equalizing the incentives to acquire information along the credit chain to prevent bottlenecks. The next proposition summarizes this discussion.

Proposition 2 (Intermediated financing capacity) *The borrowing capacity of intermediated financing through rehypothecation is given by (7), which is greater than that of direct financing given by Lemma 2. Furthermore, financing capacity of the credit chain is maximized when project outcome is uncorrelated between the two firms, i.e., $\phi = 1/2$.*

Importantly, the second firm serving as an intermediary does not impact its capacity to raise funds for its own liquidity needs. In fact, if the intermediary firm is also hit by the liquidity shock, it can raise direct financing from the end lender or pursue indirect financing with F serving as an intermediary. This creates a network of intermediation chains weaved together and intersecting one another that seems spurious but is, in fact, critical for sustaining greater borrowing capacities for all the end borrowers by diluting the chain participants agents' incentives for information acquisition.

Discussion: chains vs. multiple investors. Under a fixed information cost, an alternative theory emerges regarding the dilution of incentives to acquire information: instead of obtaining funds from one investor, the borrower can raise funds from multiple investors so that all investors have small interests at stake and weak incentive to examine the asset. Such dilution differs from our theory of dilution through intermediation. First, it applies to equity as well as debt, but in contrast, our theory is uniquely about debt as probabilistic asset ownership and credit intermediation. Second, if there is only one investor who has funds, or if the asset is not divisible, then an intermediation chain can be formed still to cave up asset ownership. In particular, even an agent without funds to lend, without superior technology, and without superior information or expertise can still join the chain as an intermediary and improve credit capacity as long as the agent's survival is not perfectly correlated with the borrower's survival.

4 Intermediation Networks

Intermediation emerges endogenously in the presence of two firms, with one firm as the ultimate borrower and the other as an intermediary. If we introduce a third firm as another intermediary, the end lender's incentive to produce information can be further diluted. Since many firms can borrow and at the same time serve as intermediaries, there may exist several intermediation chains that combine to form a complex network characterized by a seemingly spurious flow of funds between firms that make distinct investments in their projects but also channel funds to one another, being the ultimate borrowers and intermediate lenders on several chains at the same time.

Involving many firms in intermediation dilutes each funding provider's "share" of the collateral asset along the chain: each participant on the chain only owns the collateral asset with a small probability, so the incentive to produce costly information is weak. Such informational diversifi-

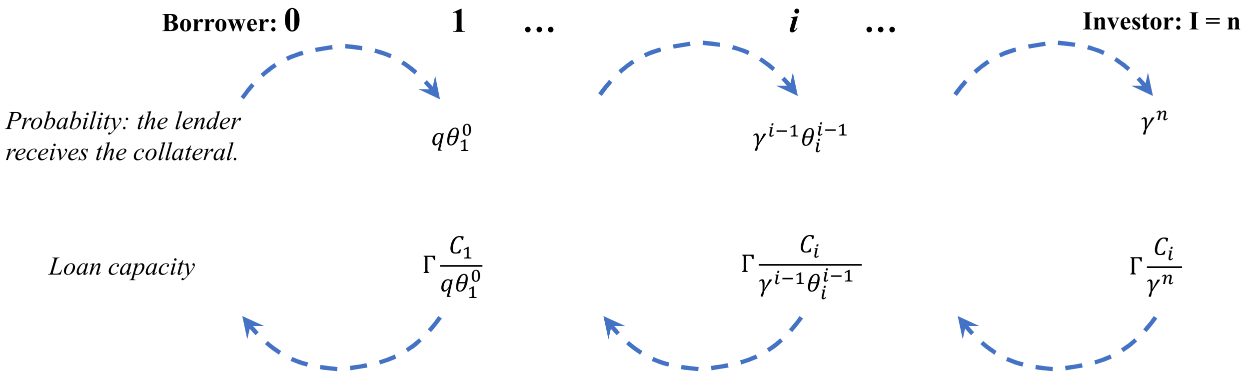

Figure 3: **A Chain with n Intermediaries.**

cation is across lenders along the intermediation chain rather than projects. Next, we characterize the optimal chain length and the optimal allocation of intermediaries along the chain.

4.1 Optimal Chain Length

Figure 3 illustrates a chain with n lenders ($n-1$ intermediaries and the end lender). To systematically present our analysis, we expand our notations as follows. Let "0" index the ultimate borrower. We use numbers to represent the intermediaries between 0 and the end lender or investor ("I"). Let γ^{i-1} denote the probability that the borrower defaults and all the first i intermediaries default, with the initial condition $\gamma^0 = q$. Let ϕ_1^0 denote Intermediary 1's default probability conditional on the borrower's default. Let ϕ_2^1 denote Intermediary 2's default probability conditional on both the borrower's default and Intermediary 1's default. In general, ϕ_i^{i-1} is the probability of the i-th intermediary's default conditional on the borrower's default and all the preceding $i-1$ intermediaries' default, and $\theta_i^{i-1} = 1 - \phi_i^{i-1}$ is the i-th intermediary's conditional survival probability. Finally, let C_i denote the i-th intermediary's information cost. The end lender's information cost is C_I.

In the following, we characterize the necessary condition for an intermediary to be included when an intermediation chain is extended, and then we proceed to characterize how the optimal chain is formed (where to locate the intermediary within the chain) to maximize the borrower's financing capacity. Consider the shortest intermediation chain (0, 1, I). It is clear that if $\Gamma \min\left\{\frac{C_1}{\gamma^0\theta_1^0}, \frac{C_I}{\gamma^0\phi_1^0}\right\} > \bar{U}$—that is, credit capacity of the chain, (0, 1, I), already reaches the full pledgeable value—adding another intermediary is unnecessary; otherwise, consider inserting Intermediary 2 between 0 and 1 or between 1 and the investor I.

The key is to identify the bottleneck, the link that channels the lowest credit needed to avoid information. If the bottleneck is (0, 1), i.e., $\frac{C_1}{\gamma^0\theta_1^0} < \frac{C_I}{\gamma^0\phi_1^0}$, the second intermediary should be inserted in the edge (0, 1), as inserting it in the edge (1, I) does not enlarge credit capacity in the chain. To see this, consider inserting the second intermediary in (1, I) to form a new chain, (0, 1, 2, I), which has credit capacity, $\min\left\{\Gamma\frac{C_1}{\gamma^0\theta_1^0}, \Gamma\frac{C_2}{\gamma^0\phi_1^0\theta_2^1}, \Gamma\frac{C_I}{\gamma^0\phi_1^0\phi_2^1}\right\}$. The original chain, (0, 1, I), has capacity $\min\left\{\Gamma\frac{C_1}{\gamma^0\theta_1^0}, \Gamma\frac{C_I}{\gamma^0\phi_1^0}\right\} = \frac{C_1}{\gamma^0\theta_1^0}$ when the bottleneck is (0, 1).[11] Under $\frac{C_1}{\gamma^0\theta_1^0} < \frac{C_I}{\gamma^0\phi_1^0}$, the third term in $\min\left\{\frac{C_1}{\gamma^0\theta_1^0}, \frac{C_2}{\gamma^0\phi_1^0\theta_2^1}, \frac{C_I}{\gamma^0\phi_1^0\phi_2^1}\right\}$ is irrelevant, because $\frac{C_1}{\gamma^0\theta_1^0} < \frac{C_I}{\gamma^0\phi_1^0}$ implies that the first term is smaller than or equal to the third term under $\phi_2^1 \in [0, 1]$. Therefore, the comparison is between $\min\left\{\frac{C_1}{\gamma^0\theta_1^0}, \frac{C_2}{\gamma^0\phi_1^0\theta_2^1}\right\}$ and $\frac{C_1}{\gamma^0\theta_1^0}$. The former is clearly dominated, implying that inserting the second intermediary in (1, I) when the bottleneck is (0, 1) does not enlarge credit capacity.

Once the bottleneck is identified and it is clear where the new intermediary is inserted, the next question is what criteria should the new intermediary meet for the extended chain to achieve a greater credit capacity? Consider a chain with n-1 intermediaries. We introduce the following assumption: for any k-th intermediary on the chain ($k \leq n-1$), its probability of survival conditional on the borrower's default and preceding k-1 intermediaries' default is not larger than its probability of survival conditional on the borrower's default, all preceding k-1 intermediaries' default, and the new intermediary's default. This is intuitive: when more intermediaries default (i.e., adding the new intermediary's default into the conditioning event), the economic environment is likely worse, so the conditional survival probability cannot increase. The next proposition summarizes the condition for a chain extension that enlarges credit capacity. The proof is in Appendix C.

Proposition 3 (Chain extension) *If the current intermediation chain with n-1 intermediaries has not maximized financing capacity to the full pledgeable value $\bar{U}$, the addition of the n-th interme-*

[11] Note that the credit capacity, $\min\left\{\Gamma\frac{C_1}{\gamma^0\theta_1^0}, \Gamma\frac{C_I}{\gamma^0\phi_1^0}\right\}$, is the same as the expression in (7) except that the notations differ—that is, γ^0, θ_1^0, and ϕ_1^0 have replaced q, $1-\phi$, and ϕ, respectively in (7).

diary to the bottleneck (i, i+1), $i \leq n-1$, enlarges credit capacity if

$$\frac{C_n}{\theta_n^i} > \frac{C_{i+1}}{\theta_{i+1}^i}. \tag{9}$$

In the inequality (9), θ_n^i is the probability of the newly inserted intermediary n's survival conditional on the borrower's default and the default of all the intermediaries from 1 to i (i.e., conditional on the collateral reaching the new intermediary), and θ_{i+1}^i is the conditional probability of Intermediary $i+1$'s survival. The condition has an intuitive interpretation: inserting the new intermediary enlarges credit capacity (widens the bottleneck) if its information cost is higher or its survival probability conditional on receiving the collateral is lower. Both forces make the new intermediary's incentive to acquire information weaker than that of the current bottleneck lender, the i+1-th intermediary. Note that this condition also points out a special case where only one intermediary is needed: when all have the same θ and the same C, only one intermediary is inserted between the borrower and the end lender, because the first intermediary is always the bottleneck.

After this new intermediary is added, the chain now has the borrower 0, the n intermediaries, and the end lender. The intermediaries are relabeled from the one closest to 0 as 1 to the one closet to the end lender as n. The labels of the first i intermediaries do not change, the newly added intermediary becomes Intermediary i+1, and the other existing intermediaries' labels are plus one. Then, if the chain has not maximized financing capacity to the full pledgeable value $\bar{U}$, it can be further extended provided that a new intermediary meeting the criterion (9) can be found.

Discussion: distributing asset ownership vs. risk. Forming intermediation chains introduces additional randomness—that is, each intermediary's survival is not perfectly correlated with others' survival; otherwise, under perfect correlation, once the borrower defaults, the intermediaries become insolvent as well, so the lender receives the asset, which then implies that the lender's incentive to produce information is just as strong as the case without any intermediation. Introducing such randomness caves up the probabilistic asset ownership (i.e., the expectation of receiving the asset or the "first moment") and thereby dilutes the expected profits from costly information acquisition among the chain participants. While the additional randomness may result in the accumulation of higher moments, this is not what agents are concerned about in our model as they are risk-neutral. Typically, financial networks are formed to distribute risk. Our financial networks are formed to distribute ownership. The assumption of risk-neutrality highlights such distinction.

4.2 Optimal Intermediary Sequencing

In the following, we assume that the chain does not maximize financing capacity to the full pledgeable value, $\bar{U}$, so whether to extend the chain depends on whether intermediaries that satisfy the condition (9) can be found. When multiple intermediaries satisfy this condition, which one to include remains an open question. Inserting an intermediary affects whether and which intermediaries will be included afterward. A local optimum may not be the global optimum. More generally, how should intermediaries be positioned on the chain to maximize the financing capacity?

To tightly characterize the optimal chain and demonstrate the key economic forces, we consider a simplified setting with conditionally independent intermediaries: Intermediary k's probability of survival conditional on 0's default, $\theta(k)$, is a univariate function of its index k, and

$$\theta(k) = \mathbf{Prob}(survival|0\text{'s default}) = \mathbf{Prob}(survival|0\text{'s default \& any intermediaries' default}).$$

Conditional on the borrower 0's default, intermediaries have different default probabilities but their default is independent. Note that the index k is assigned to differentiate intermediaries, and this index may differ from the intermediaries' ranking on the chain (i.e., how close they are to the borrower 0), which can change when more intermediaries are added. Intermediaries also differ in information cost. Let $C(k)$ denote intermediary k's information cost.

When intermediary k is the i+1-th intermediary, the financing capacity of the edge (i, i+1) is $\Gamma \frac{C(k)}{\gamma^i \theta(k)}$. Because the bottleneck of a chain determines its financing capacity, the optimal chain should order intermediaries such that $\Gamma \frac{C(k)}{\gamma^i \theta(k)}$ is equalized along the chain. The intuition is similar to production maximization under a Leontief production function. Note that ordering intermediaries affects γ^i. Therefore, baring any integer constraint, the optimal chain should feature

$$\frac{C(k)}{\gamma^{i(k)}\theta(k)} = \frac{C(k')}{\gamma^{i(k')}\theta(k')}, \tag{10}$$

where $i(\cdot)$ is the ordering function with, for example $i(k) = 2$ meaning that intermediary k is the second intermediary (i.e., the third participant on the chain). Rearranging the equation, we obtain

$$\frac{\gamma^{i(k)}}{\gamma^{i(k')}} = \frac{C(k)/\theta(k)}{C(k')/\theta(k')}. \tag{11}$$

Therefore, we conclude that, for an intermediary with a lower $C(k)/\theta(k)$, its $\gamma^{i(k)}$ should be lower. The next proposition summarizes this result.

Proposition 4 (Intermediary sequencing condition) *The optimal sequencing of intermediaries, i.e., the intermediary-ordering function $i(\cdot)$, satisfies the condition (11).*

Intuitively, two intermediaries may have the same incentives to acquire information despite different information costs. Intermediaries with a high information costs can face a high probability of ending up with the collateral without triggering information acquisition. The same is the case for an intermediary with low information costs but low probability of ending up with the collateral. Next, we show how intermediaries are ranked along the chain. In Appendix D, we demonstrated how the optimally sequenced chain emerges endogenously in a laissez-faire environment.

Homogeneous conditional survival probability. Consider the special case of all intermediaries having the same survival probability, i.e., $\theta(k) = \theta \in (0, 1)$ for all k, which then implies that $\gamma^{i(k)} = q(1-\theta)^{i(k)-1}$. Therefore, the condition (11) above can be simplified to

$$\frac{(1-\theta)^{i(k)-1}}{(1-\theta)^{i(k')-1}} = \frac{C(k)}{C(k')}. \tag{12}$$

Taking logarithm on both sides, we obtain

$$i(k) - i(k') = \frac{\ln C(k) - \ln C(k')}{\ln(1-\theta)}. \tag{13}$$

Note that $\ln(1-\theta) < 0$ because $\theta \in (0,1)$. Therefore, we arrive at the following corollary: for intermediaries with low information costs, the probability of it receiving the collateral—the joint probability of the borrower 0's default and all preceding intermediaries' default, $\gamma^{i(k)}$—should be sufficiently low to dampen the incentive of information production.

Corollary 1 (Optimal sequencing under homogeneous θ) *Under $\theta(k) = \theta \in (0,1)$, an intermediary k with a lower information cost is placed later in the optimal chain, i.e., $i(k)$ is higher.*

Homogeneous information cost. Next, we consider another simplified setting. Instead of heterogeneous $C(k)$ and homogeneous θ, we consider the same C and heterogeneous $\theta(k)$, hence heterogeneous conditional default probability, $\phi(k)$.

For any k and k', the "Leontief" condition can be simplified to:

$$\gamma^{i(k)}\theta(k) = \gamma^{i(k')}\theta(k'). \tag{14}$$

Note that $\gamma^{i(k)} = q\prod_{i(j)<i(k)}\phi(j)$, where, as previously discussed, $i(\cdot)$ is the ordering function, and $\prod_{i(j)<i(k)}\phi(j)$ is the joint probability of all intermediaries between B and $i(k)$ defaulting conditional on F's default. Therefore, the condition can be simplified to

$$\prod_{i(j)<i(k)}\phi(j)\theta(k) = \prod_{i(j)<i(k')}\phi(j)\theta(k'). \tag{15}$$

Let $\underline{i}(k,k') = \min\{i(k), i(k')\}$, which is a function derived from the ordering function $i(\cdot)$. If, for instance, $i(k') = \underline{i}(k,k')$, then the condition can be further simplified to

$$\theta(k) = \prod_{i(k)\le i(j)<i(k')}\phi(j)\theta(k') < \theta(k'), \tag{16}$$

as $\prod_{i(k)\le i(j)<i(k')} < 1$. Therefore, the conclusion we draw is that intermediaries with lower survival probability conditional on F's default precede those with higher probability on the optimal chain.

Corollary 2 (Optimal sequencing under homogeneous C) *Under $C(k) = C$, an intermediary k*

with a higher conditional (on F's default) survival probability, $\theta(k)$, is placed later in the optimal chain, i.e., $i(k)$ is higher.

Intuitively, the optimal chain pushes intermediaries with high survival probabilities downstream, closer to the end lender, so that the probability for it to end up with the collateral—the joint probability of F's default and all the preceding intermediaries' default—is low and can counteract its (high) conditional survival probabilities. Doing so evenly distributes the force of probability dilution along the chain, in line with the "Leontief" condition (10), so that each chain participant's share of the collateral is low in expectation and each participant's incentive to produce information is equally weak, avoiding a bottleneck on the chain.

5 Specialized Funding Intermediaries

So far, our analysis has focused on financing firms' liquidity needs at $t = 1$. Next, we consider firms' investment decisions at $t = 0$. Specifically, we extend our model by allowing firms to either invest in the project (illustrated in Figure 1) or hold risk-free government bonds. Throughout our analysis, we assume the condition (4) holds, and accordingly, we focus on information-insensitive debt as the preferred financing contract. We also assume that the IC constraints for information-insensitive debt bind for direct financing and across different forms of intermediated financing.

The bond is a storage technology: for each unit of goods invested at $t = 0$, the investor can obtain one unit of goods either at $t = 1$ or 2. A firm invests in the project if the project return is greater than the bond return; otherwise the firm holds its endowment K in the bond. We assume that across all financing arrangements in the liquidity event at $t = 1$, the return from investing in a project is greater than one. One would expect the bond return, r^b, to be equal to one, so no firm would hold the bond. This argument ignores that bond holdings may facilitate intermediation.

As in Section 3, we consider a setting with two firms. We assume a firm holding bonds faces a cost of acquiring information on the other firm's project that is equal to $\bar{C} > C$. Intuitively, by specializing in bonds investments, the firm relinquishes expertise about projects. In contrast, the investor, whose information cost is C, may have exposure to more broad asset classes and thus has a stronger expertise. A firm specializing in bonds can be viewed as a money market fund that specializes in relatively safe fixed-income securities, while the investor can be a universal bank, an asset management firm, or other investors that have research capacity in riskier assets and projects. Therefore, choosing to invest in the bond (or to be "narrow") is to stay ignorant. We will show that by raising its own information acquisition cost, the firm can channel more funds for the other firm.

Our goal is to characterize a set of conditions under which an equilibrium exists where one firm invests in the project while the other holds the bond and serves as a funding intermediary.

For the project-investing firm, it faces two financing options when hit by the liquidity shock at $t = 1$: 1) direct financing with capacity L^d, where the superscript "d" is for "direct"; 2) financing intermediated by the bond-investing firm with capacity, L^b. In the first option, $L^d = \Gamma C/q$ (see Lemma 2). If the firm pursues the second option, the other firm can raise funds worth K from the end lender, pledging its bond holdings as collateral, and under the assumption (1), $K > \bar{U}$, so the intermediary has enough funds to supply the project-investing firm. The bond-holding intermediary can lend $L^b = \Gamma\bar{C}/q$. Because the intermediary holds the bond, it does not go bankrupt. The probability it receives the asset is simply the project-investing firm's default probability q.

Therefore, when reaching out to the bond-holding firm as funding intermediary, the project-investing firm's outside option is L^d, and the difference between option 1 and 2 is given by

$$L^b - L^d = \Gamma\frac{(\bar{C} - C)}{q} > 0. \tag{17}$$

Here, different from Section 3, the role of intermediary is no longer to dilute the probabilistic asset ownership. Inserting a bond-holding intermediary enlarges financing capacity because it insulates the underlying asset from the relatively more informed end lender who is more tempted to produce costly information. In other words, the intermediary acts as an information barrier.

Specialization in bond investments plays two roles. First, it allow the firm to obtain funds at $t = 1$ from the end lender frictionlessly so that it has enough funds to supply the project-investing firm, as previously discussed. Second, it raises this intermediary firm's information cost.

The financing wedge above translates into an expected surplus creation at $t = 0$ given by

$$S^b = \lambda[(1-q)A - 1](L^b - L^d) = [(1-q)A - 1]\Gamma \frac{(\bar{C} - C)}{q}, \tag{18}$$

where λ is the probability of liquidity shock and financing needs, and, as discussed in Section 2, $(1-q)A - 1$ is the expected profits from investing at $t = 1$ in the liquidity event. Let h denote the fraction of surplus seized by the bond-holding intermediary firm.[12]

We can compute the expected return of the intermediary firm's bond holding at $t = 0$:

$$r^b = \frac{K + hS^b}{K} = 1 + \lambda h[(1-q)A - 1]\widehat{\Gamma} \frac{(\bar{C} - C)}{q}, \tag{19}$$

where $\widehat{\Gamma}$ is defined as follows

$$\widehat{\Gamma} = \frac{\Gamma}{K} = \frac{1}{p\left(\frac{G - \bar{U}}{\bar{U}}\right) K}. \tag{20}$$

The bond return has two components. First, it's a store of value, and second, it allows the bold-holding firm to earn an intermediation profit that is h fraction of the surplus created from improving the other firm's financing condition (relative to directly raising funds from the end lender). The intermediation profit is greater when the information-cost wedge, $\bar{C} - C$, is wider—that is, when holding the bond allows the intermediary firm to be even more ignorant than the end lender.

Let r^p denote the project return and V^d the expected value of project under direct financing (the outside option) in the liquidity event at $t = 1$. The other (project-investing) firm's return is

$$r^p = \frac{V^d + (1-h)S^b}{K}. \tag{21}$$

which consists of a baseline return V^d/K under direct financing in the liquidity event (i.e., the outside option) and $1 - h$ fraction of the surplus from financing intermediated by the bond-holding

[12]In Section 3, the surplus created by indirect financing relative to direct financing goes to the ultimate borrower. Here we consider a more general case where the surplus can be split between the borrower and funding intermediary.

firm. The expected project value under direct financing in the liquidity event is given by

$$V^d = \bar{U} + \lambda \left[(1-q)A - 1\right] L^d + (1-\lambda)(1-q)AK, \tag{22}$$

As shown in Figure 1, the project has an expected liquidation value $\bar{U}$ across all event branches. When the liquidity shock hits, which happens with probability λ, the firm spends L^d (funds raised via direct financing), with L^d given by Lemma 2, and then, with probability $1-q$, the productivity A materializes. In the absence of liquidity shock, which happens with probability $1-\lambda$, the project runs on itself and delivers productivity A with probability $1-q$.

In equilibrium, both firms should be indifferent between investing in the bond and investing in a project, i.e., $r^b = r^p$, or equivalently, the bond-holding firm's share of surplus is

$$h = \frac{1}{2} + \left(\frac{V^d - K}{2S^b}\right). \tag{23}$$

For the equilibrium to exist, the bond return must be sufficiently high such that the bond-holding firm does not deviate to investing in a project, i.e., $r^b \geq V^i/K$, or equivalently,

$$h \geq \frac{V^i - K}{S^b}, \tag{24}$$

where V^i is the project value under indirect financing in the liquidity event,

$$V^i = \bar{U} + \lambda \left[(1-q)A - 1\right] L^i + (1-\lambda)(1-q)AK,$$

and L^i is given by (7) because when the bond-holding firm deviates, both firms invest in projects and intermediate for each other as in Section 3. Finally, we verify that the project-investing firm does not deviate to holding the bond. This is obvious: deviation means both firms holding the bond and no need for intermediation at $t = 1$, which implies $r^b = 1$ below the project return (> 1).

This equilibrium with one firm investing in the bond and the other in a project dominates the equilibrium in Section 3 where both firms invest in projects and intermediate funding supply for one another if the following condition holds,

$$K + V^d + S^b > 2V^i, \tag{25}$$

where the left side is the sum of two firms' values including the bond value as storage for one firm (K), project value under direct financing in the liquidity event for the other firm (V^d), and surplus created by the bond-holding firm intermediating financing for the project-investing firm (S^b). The next proposition summarizes this result.

Proposition 5 (Intermediated financing facilitated by bond) *The equilibrium with one firm investing in the bond and the other in a project exists with h given by (23) if the condition (24) holds. If the condition (25) holds, it dominates the equilibrium where both firms invest in projects.*

In summary, our paper demonstrates two forms of financial intermediation under costly information production. In Section 3, our focus is on intermediation (or a chain of debt) as a way to dilute the probabilistic asset ownership that debt carries intrinsically. The analysis takes as given firms' assets. In this section, we show that intermediation, when combined with endogenous asset choice, enlarges credit capacity because uninformed intermediaries serve as information barriers.

6 Conclusion

A lender is willing to "lend in the dark" when the likelihood of ending up with the asset is low. While a lender ends up owning the asset only when the borrower defaults, an equity investor always owns it. Since producing information is more beneficial when the likelihood of owning the asset increases, an equity investor has a stronger incentive to produce information than a debt investor. Therefore, when information production is costly, information-insensitive contracts are preferred, and among those debt generates a greater financing capacity. Hence, in the pecking order of financing instruments, information-insensitive debt tends to be at the top.

Intermediation networks arise endogenously because they can dilute the incentives to produce information even further. This happens because the joint probability of the end borrower and all the preceding lenders' defaulting is smaller than the single probability of the borrower's default, so the incentive to produce information is reduced—that is, credit channeled through seemingly spurious and unnecessary chains of intermediation is larger than with direct financing. This role of intermediation may induce certain firms to specialize in obtaining assets, such as government bonds, that in principle have lower returns but are valuable to serve as intermediary to "grease" the flow of credit within the chain. We have also characterized the anatomy of this information-concealing credit architecture. We show that the length of intermediation chains and the sequencing of intermediaries within the chain is optimal and depends on the correlation structure of intermediaries' asset correlations and their information acquisition costs.

Our model can be applied to understand various forms of debt contracts and intermediation, for example, repurchase agreements (repo) and rehypothecation. Repo contracts require the borrower's asset to be transferred to the lender on the spot and transferred back when the debt is repaid, while other debt contracts channel funds to the borrower on the spot and only transfer the asset in bankruptcy. The timing of collateral transfer is inconsequential in our model. When applying our model to repo, requiring the backing asset to be transferred on the spot, in which case the intermediary channels both funds and collateral, is only for interpreting the intermediated credit flow as repo and collateral intermediation (rehypothecation). Our model shows that a repo chain, including the end borrower, an intermediary, and the end lender, distributes the probability of asset possession between the intermediate and end lenders. Therefore, repo chains and collateral rehypothecation are mechanisms for diluting lenders' incentives to produce costly information.

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A Optimal Equity Contracts: Proof of Lemma 1.

A.1 Information-sensitive equity

The firm offers a contract to the investor that specifies the equity price of k_U^s for z_U^s fraction of equity shares, where $U \in \{B, G\}$ and the superscript represents the type of financing contract ("s" for information-sensitive). After the investor acquires information at the cost of C, the value of U is revealed to her and to the firm, and the U-contingent contract is executed. For the investor to participate, the break-even condition must hold:

$$pz_G^s(G - k_G^s - C) + (1-p)z_B^s(B - k_B^s - C) = 0. \tag{A.1}$$

It is assumed that the investor breaks even in expectation and all the surplus goes to the firm.

Given Assumption 1 (i.e., A is sufficiently high), the optimal fraction of share issuance is $z_G^s = z_B^s = 1$. The values of E_B^s and E_G^s hence represent the financing the firm can obtain to continue operations if the liquidation value is low or high, respectively. Given the linearity of the constraint, these are indeterminate, so we normalize $E_B^s = B$, which simply implies that the cost of information acquisition is ex-ante compensated if the liquidation value is G. The investor's break-even condition (A.1) implies $k_G^s = G - C/p$. In words, given a sufficiently high A, the firm is willing to sell the liquidation value that is worth G at a discounted price $k_G^s = G - C/p$ so that the investor breaks even in expectation, taking into account the cost of information production. Note that the cost of information production reduces the firm's financing capacity: under $U = G$, the funds raised are k_G^s, which is below G (the pledgeable liquidation value of the firm's stock).

We assume the firm keeps the full surplus, which is equal to

$$(1-q)\left[p(Ak_G^s - G) + (1-p)(Ak_B^s - B)\right] + q(0 - \bar{U}), \tag{A.2}$$

where $Ak_G^s - G$, for instance, captures the profits from obtaining funds selling the asset with high liquidation value and continuing operations at a scale E_G^s,with a nonpledgeable return A in case the project succeeds, with probability $1-q$. This scenario happens with probability p and the corresponding situation with low liquidation value with probability $1-p$. If the project fails, the firm loses the liquidation value to the investor. Substituting $E^s_B = B$ and $k^s_G = G - C/p$ into the social surplus, we obtain the following result.

Social surplus. The optimal information-sensitive equity contract generates social surplus $[(1-q)(A-1)-q]\bar{U} - (1-q)AC$. The first part of the surplus, $[(1-q)(A-1)-q]\bar{U}$, shows that it is increasing in the expected pledgeable value, $\bar{U}$. Consistent with our assumption of a sufficiently high A, we maintain $(1-q)(A-1)-q > 0$ through the paper. The second term, $-(1-q)AC$, shows that the cost of information production reduces the surplus by reducing financing capacity and wasting resources on producing information. The cost is higher when the project is more productive, i.e., A is higher, and when it is more likely to succeed, i.e., $1-q$ is higher.

A.2 Information-insensitive equity

The firm offers to sell equity at price E^i for a z^i fraction of the liquidation (pledgeable) value, where the superscript, "i", represents information-insensitive. Notice that in this case, there is no subscript as the contract is by construction not conditional on the true liquidation value. For this contract to be feasible, it should be the case that the investor does not have an incentive to deviate and privately learn about U at the cost of C. The equity price, E^i, is set so that the investor breaks even based on the expected liquidation value:

$$E^i = z^i\bar{U} = z^i[pG + (1-p)B]. \tag{A.3}$$

The investor does not privately produce information if its expected return(the left side below) is lower than the expected return of following the contract without information acquisition (zero profit on the right side below):

$$(1-p)(0-C) + p(z^iG - E^i - C) \leq 0. \tag{A.4}$$

On the left side, the first term represents the case of $U = B$ where the investor will not buy equity as the payout is below the price, $z^iB < E^i = z^i\bar{U}$, and the second term represents the gain of knowing privately $U = G$ but buying equity at the lower uncertainty price. Rearranging this incentive-compatibility (IC) condition and substituting out E^i using (A.3), we obtain

$$E^i = z^i\bar{U} \leq \frac{C}{p\left(\frac{G-\bar{U}}{\bar{U}}\right)}, \tag{A.5}$$

where the right side is a limit on the amount of information-insensitive equity financing the firm can raise. Intuitively, if the information cost is low or the liquidation (pledgeable) value is information worthy (i.e., the percentage deviation of G from $\bar{U}$ is high), the investor is tempted to produce information, so the information-insensitive financing capacity is low. We consolidate such properties of the pledgeable value into one parameter, Γ, given by

$$\Gamma = \frac{1}{p\left(\frac{G-\bar{U}}{\bar{U}}\right)}, \tag{A.6}$$

so that the IC constraint on financing capacity can be written as

$$E^i = z^i\bar{U} \leq \Gamma C, \tag{A.7}$$

where Γ summarizes the attributes of the pledgeable value that induce information and C is the cost of such information. The lower Γ and C, the higher the incentives to learn about the asset, and the stronger the constraint in raising funds with an information-insensitive equity contract.

The surplus from this contract, which is the information-insensitive counterpart of (A.2), is

$$(1-q)(AE^i - z^i\bar{U}) + q(0 - z^i\bar{U}), \tag{A.8}$$

When $E^i = \bar{U}$ (i.e., the IC constraint (A.7) is not binding at $z^i = 1$), the social surplus is greater than that given by (A.2) under information-sensitive equity financing. However, the maximum financing capacity $\bar{U}$ may not be attainable under the IC constraint (A.7).

Social surplus. The optimal information-insensitive equity contract is subject to the IC constraint (A.7) that limits z^i, the fraction of equity sold to the investor. Given z^i, it generates social surplus $[(1-q)(A-1)-q]z^i\bar{U}$ in the liquidity event. Note that as long as the investor's break-even condition holds, the information-sensitive contract is feasible. The information-insensitive contract requires the additional IC condition (A.7).

B Optimal Debt Contracts: Proof of Lemma 2.

B.1 Information-sensitive debt

The timing is the same as the case of the equity contract. The firm offers a contract that is U-contingent. After receiving the contract, the lender produces information on U, and U is also revealed to the firm. Then the contract is executed under $U = B$ or $U = G$. Information-sensitive debt is feasible as long as the lender's break-even condition holds.

The debt contract is summarized by three variables. The lending amount is denoted by L_U^s, the repayment to the lender is denoted by R_U^s, and the fraction of collateral or liquidation value the lender seizes in default is denoted by x_U^s, where $U \in \{B, G\}$. In the following, we characterize the optimal contract step-by-step.

Given the assumption that A is sufficiently high, and that the firm wants to borrow as much as possible, we set $x_B^s = x_G^s = 1$, This is the firms wants to pledge as much collateral as possible.

Whether the project fails or not is the firm's private information, so the firm may default even if it succeeds.[1] Therefore, a debt contract must induce the firm to tell the truth, and hand the collateral over only when it cannot repay. The truth-telling condition requires $R_G^s = G$ and $R_B^s = B$. Note that for the equity contract, we do not discuss this issue because whether the project fails or succeeds, the lender receives the same payoff given by the liquidation (pledgeable) value.

The lender's break-even (participation) condition equates the expected loan minus the infor-

[1]Note that verifying project outcome is not an issue for equity financing because, whether the project succeeds or fails, the equity investor's share is predetermined.

mation costs with the expected repayment and default proceedings.

$$pL^s_G + (1-p)L^s_B + C = (1-q)[pR^s_G + (1-p)R^s_B] + q[px^s_G G + (1-p)x^s_B B]. \tag{B.9}$$

Replacing full collateral pledged ($x^s_B = x^s_G = 1$) and truth-telling conditions ($R^s_G = G$ and $R^s_B = B$), we can rewrite the participation constraint as :

$$pL^s_G + (1-p)L^s_B + C = pG + (1-p)B = \bar{U}. \tag{B.10}$$

The payments in the two states, $U = B$ and G, are indeterminate, so we fix $L^s_B = B$, and obtain

$$pL^s_G + C = pG, \text{ or, equivalently, } L^s_G = G - \frac{C}{p}. \tag{B.11}$$

Therefore, we have fully characterized the U-contingent debt contract (L^i_G, R^i_G, x^i_G) and (L^i_B, R^i_B, x^i_B). For $U = G$, we have $L^s_G = G - \frac{C}{p}$, $R^s_G = G$, and $x^G_s = 1$, and for $U = B$, $L^s_B = B$, $R^s_B = B$, and $x^F_s = 1$. Even though collateral is fully pledged, the expected credit capacity is below the expected liquidation value by the cost of information C.

Social surplus. The social surplus created by the information-sensitive debt is given by

$$p(1-q)\left[AL^s_G - (1-q)R^s_G - qx^s_G G\right] + (1-p)(1-q)\left[AL^s_B - (1-q)R^s_B - qx^s_B B\right]. \tag{B.12}$$

The optimal information-sensitive debt contract generates social surplus $[(1-q)(A-1)-q]\bar{U} - (1-q)AC$ in the liquidity event.

B.2 Information-insensitive debt

Next, we consider the scenario in which the lender lends based on the expected liquidation value, and it is incentive-compatible for lender not to produce costly information. Without information on liquidation value, U, the debt contract is no longer contingent on the value of U. It specifies the amount of lending, L^i (the superscript "i" is for information-insensitive), the fraction of liquidation value seized by the lender when the project fails, x^i, and the nominal repayment, R^i. The lender's break-even (participation) condition is,

$$L^i = (1-q)R^i + qx^i[pG + (1-p)B], \tag{B.13}$$

and the firm's truth-telling condition,

$$R^i = x^i[pG + (1-p)B]. \tag{B.14}$$

From the borrower's truth-telling condition, we obtain

$$x^i = \frac{R^i}{pG + (1-p)B} = \frac{R^i}{\bar{U}} \leq 1, \tag{B.15}$$

where the last inequality captures that the firm cannot pledge more than the whole collateral. Substituting this solution of x^i into the lender's participation (break-even) condition, we obtain

$$L^i = R^i. \tag{B.16}$$

After the firm proposes the debt contract, the lender decides whether to produce information and whether to accept the offer. Therefore, the contract design is subject to the following incentive compatibility constraint:

$$0 \geq (1-p)(0-C) + p[(1-q)R^i + qx^iG - L^i - C]. \tag{B.17}$$

The left side represents the case without information production as the lender breaks even and earns zero profit. On the right side, if $U = B$, the lender will not lend to the firm as the expected payoff is smaller than the specified lending amount, as shown below:

$$qR^i + (1-q)x^iB = L^i\left[q + (1-q)\frac{B}{\bar{U}}\right] < L^i,$$

where we apply (B.16) to substitute out R^i and x^i in the first step If $U = G$, the lender will accept the offer, generating positive profits. The positive profits under $U = G$ are directly implied by the break-even in expectation and the loss from lending under $U = B$. Thereby, we have confirmed that under $U = B$, the lender declines the offer, and under $U = G$, the lender accepts the contract.

The incentive compatibility (B.17) constraint can be simplified to the following inequality that is at the heart of our model and carries several key messages:

$$L^i \leq \frac{C}{qp\left(\frac{G-\bar{U}}{\bar{U}}\right)} = \Gamma\frac{C}{q}, \tag{B.18}$$

where we use Γ, defined in (A.6), to summarize the attributes of the project's collateral. As with equity, the left side (financing capacity) is high when it is costly for the lender to acquire information (high C) or the asset does not induce information (high Γ). Importantly, however, with a debt contract, credit capacity is also high when the probability the project fails is low (low q). This is not due to the lender's risk aversion and credit risk being priced in equilibrium. In our model, the lender is risk-neutral. The link between default probability and credit capacity emerges from the lender's information choice. When q is low, it is unlikely that the firm defaults and the lender ends up in possession of the asset, discouraging its examination.

Since A is sufficiently high, the constraint (B.18) binds, and we have fully characterized the information-insensitive debt contract, (L^i, R^i, x^i):

$$L^i = \min\left\{\bar{U},\, \Gamma\frac{C}{q}\right\}, \qquad R^i = L^i, \quad \texttt{and} \quad x^i = R^i/\bar{U}. \tag{B.19}$$

Social surplus. The social surplus, i.e., the firm's profit, is

$$(1-q)(AL^i - R^i) + q(0 - x^i\bar{U}) = [(1-q)(A-1) - q]L^i. \tag{B.20}$$

The optimal information-insensitive debt contract is subject to the IC constraint (B.18) that limits L^i, the amount of lending. Given L^i, it generates surplus $[(1-q)(A-1)-q]L^i$ in the liquidity event.

C Proof of Proposition 3

Consider the bottleneck of chain (0, 1, I) being (1, I), i.e., $\min\left\{\frac{C_1}{\gamma^0\theta_1^0}, \frac{C_I}{\gamma^0\phi_1^0}\right\} = \frac{C_I}{\gamma^0\phi_1^0} < \frac{C_1}{\gamma^0\theta_1^0}$. Inserting Intermediary 2 to form (1, 2, I) enlarges financing capacity if and only if

$$\min\left\{\frac{C_2}{\gamma^0\phi_1^0\theta_1^0}, \frac{C_I}{\gamma^0\phi_1^0\phi_2^1}\right\} > \frac{C_I}{\gamma^0\phi_1^0}.$$

Given that $\frac{C_I}{\gamma^0\phi_1^0\phi_2^1} > \frac{C_I}{\gamma^0\phi_1^0}$ under $\phi_2^1 \in (0,1)$, inserting Intermediary 2 to extend the edge from (1, I) to (1, 2, I) enlarges financing capacity if and only if $\frac{C_2}{\gamma^0\phi_1^0\theta_2^1} > \frac{C_I}{\gamma^0\phi_1^0}$, or equivalently,

$$\frac{C_2}{\theta_2^1} > C_I. \tag{C.21}$$

Intuitively, θ_2^1 is the probability that both the borrower and Intermediary 1 default but Intermediary 2 survives and ends up holding the collateral. If $C_2 > C_I$, this inequality holds obviously; if not, this new intermediary's information cost scaled by the probability of it receiving the collateral must be sufficiently large relative to that of the end lender (investor) I's information cost.

Consider the decision to insert the n-th intermediary and the bottleneck being (i,i+1), where $i \in \{0, 1, ..., n-1\}$ with the convention $(n-1)+1$ =I for the end lender (investor). We will prove that extending the edge (i,i+1) to (i,n,i+1) by inserting the n-th intermediary enlarges credit capacity if and only if

$$\frac{C_n}{\theta_n^i} > \frac{C_{i+1}}{\theta_{i+1}^i},$$

where θ_n^i is the probability of the newly inserted intermediary's survival conditional on the borrower's default and the default of all the intermediaries from 1 to i and θ_{i+1}^i is the conditional probability of Intermediary $i+1$'s survival. This condition nests (C.21), because the conditional survival probability of the investor is equal to 1 ($\theta_I^1 = 1$) in (C.21), $\frac{C_2}{\theta_2^1} > C_I = \frac{C_I}{\theta_I^1}$.

Inserting the n-th intermediary between i and i+1 enlarges financing capacity if and only if

$$\Gamma \min\left\{\frac{C_1}{\gamma^0\theta_1^0}, \frac{C_2}{\gamma^1\theta_2^1}, ..., \frac{C_i}{\gamma^{i-1}\theta_i^{i-1}}, \frac{C_n}{\gamma^i\theta_n^i}, \frac{C_{i+1}}{\gamma^i\phi_n^i\hat{\theta}_{i+1}^i}, ..., \frac{C_{n-1}}{\hat{\gamma}^{n-2}\hat{\theta}_{n-1}^{n-2}}, \frac{C_I}{\hat{\gamma}^{n-1}\hat{\phi}_n^{n-1}}\right\} >$$
$$\Gamma \min\left\{\frac{C_1}{\gamma^0\theta_1^0}, \frac{C_2}{\gamma^1\theta_2^1}, \cdots, \frac{C_i}{\gamma^{i-1}\theta_i^{i-1}}, \quad \frac{C_{i+1}}{\gamma^i\theta_{i+1}^i}, \quad \cdots, \quad \frac{C_{n-1}}{\gamma^{n-2}\theta_{n-1}^{n-2}}, \frac{C_I}{\gamma^{n-1}\phi_n^{n-1}}\right\}$$

where $\hat{\gamma}^i$ represents the joint probability of the borrower 0's default, the first i intermediaries' default, *and* the new intermediary's default, $\hat{\phi}_{i+1}^i$ is the probability of Intermediary i+1's default conditional on the borrower 0's default, the first i intermediaries' default, *and* the newly inserted intermediary's default, and $\hat{\phi}_{i+1}^i$ is the probability of Intermediary i+1's survival conditional on the borrower 0's default, the first i intermediaries' default, *and* the newly inserted intermediary's default. As a reminder of our notation, we have, by definition, $\gamma^{n-1}\phi_n^{n-1} = \gamma^n$ and $\hat{\gamma}^{n-1}\hat{\phi}_n^{n-1} = \hat{\gamma}^n$.

This condition is essentially an IC constraint for the network to expand because we need the total surplus for those already on the chain to improve. An important insight is that inserting a new intermediary changes these probabilities for those "downstream" in the chain, but not "upstream." Since the left and right sides share the initial i items, the condition is equivalent to

$$\Gamma \min\left\{\frac{C_n}{\gamma^i\theta_n^i}, \frac{C_{i+1}}{\gamma^i\phi_n^i\hat{\theta}_{i+1}^i}, ..., \frac{C_{n-1}}{\hat{\gamma}^{n-2}\hat{\theta}_{n-1}^{n-2}}, \frac{C_I}{\hat{\gamma}^{n-1}\hat{\phi}_n^{n-1}}\right\} > \Gamma \min\left\{\frac{C_{i+1}}{\gamma^i\theta_{i+1}^i}, ..., \frac{C_{n-1}}{\gamma^{n-2}\theta_{n-1}^{n-2}}, \frac{C_I}{\gamma^{n-1}\phi_n^{n-1}}\right\}. \tag{C.22}$$

Note that, for any $k \in \{1, ..., n-(i+1)\}$, we have, by the definitions of probabilities,

$$\frac{C_{n-k}}{\hat{\gamma}^{n-k-1}\hat{\theta}_{n-k}^{n-k-1}} > \frac{C_{n-k}}{\gamma^{n-k-1}\theta_{n-k}^{n-k-1}},$$

because the events measured by $\hat{\gamma}_{n-k}^{n-k-1}$ contains one more event (the new intermediary's default) than the events measured by γ_{n-k}^{n-k-1} so $\hat{\gamma}_{n-k}^{n-k-1} \leq \gamma_{n-k}^{n-k-1}$. Next, we impose the following assumption:

$$\hat{\theta}_{n-k}^{n-k-1} \leq \theta_{n-k}^{n-k-1}. \tag{C.23}$$

The probability for Intermediary n-k to survive is lower when another intermediary (the new one) defaults. By definition, $\hat{\theta}_{n-k}^{n-k-1}$ measures the probability of survival conditional on all the preceding $n-k-1$ intermediaries' default *and* the new intermediary's default, while θ_{n-k}^{n-k-1} measures the probability of survival conditional on only the previous $n-k-1$ intermediaries' default.

An interesting property emerges: when a new intermediary is inserted into the chain, both γ and θ decrease. The former is lower because it is a joint probability and, from γ to $\hat{\gamma}$, another event is added (the new intermediary's default). The latter is lower as it is a conditional probability of survival, so according to our assumption, when more intermediaries default (i.e., adding the new intermediary's default), the economic environment is likely worse, so θ declines to $\hat{\theta}$.

Therefore, in the condition for the newly inserted intermediary to enlarge financing capacity, i.e., the inequality (C.22), from the third terms on the left side to the last term, they are all larger than the corresponding terms on the right side (i.e., the second to the last terms). Moreover, since the edge (i, i+1) is the bottleneck before we insert the n-th intermediary, we know that the right side can be simplified to just $\frac{C_{i+1}}{\gamma^i \theta_{i+1}^i}$. On the left side, we can ignore the third to last terms as they are larger than the second to last terms on the right side. So, the condition (C.22) can be simplified to

$$\min\left\{\frac{C_n}{\gamma^i \theta_n^i}, \frac{C_{i+1}}{\gamma^i \phi_n^i \hat{\theta}_{i+1}^i}\right\} > \frac{C_{i+1}}{\gamma^i \theta_{i+1}^i}, \tag{C.24}$$

where we also divide both sides by Γ. Note that $\frac{C_{i+1}}{\gamma^i \phi_n^i \hat{\theta}_{i+1}^i} \geq \frac{C_{i+1}}{\gamma^i \theta_{i+1}^i}$ because $\phi_n^i \in [0,1]$. Therefore, for the inequality to hold, we only need

$$\frac{C_n}{\theta_n^i} > \frac{C_{i+1}}{\theta_{i+1}^i}, \tag{C.25}$$

where, to simplify the expression, we divide both sides by γ^i.

D Endogenous Chain Formation

We characterize the endogenous formation of intermediation chains. To form the optimal chain, intermediaries are added one after another in a laissez-faire environment, and each step of chain extension must satisfy the condition (9) so that the financing capacity of the chain is increased and there is economic surplus created for all existing participants to share. In a way, the condition (9) is an incentive-comparability constraint for all existing chain participants to accept a new intermediary. In the following, we consider the simplified setting of conditionally independent intermediaries and, specifically, the case of homogeneous θ and the case of homogeneous $C(k)$.

Homogeneous conditional survival probability. When every intermediary has the same conditional (on the borrower 0's default) survival probability, $\theta(k) = \theta$, the condition (9) for including the n-th intermediary on an existing chain with bottleneck (i, i+1) can be simplified to

$$\frac{C_n}{\theta_n^i} > \frac{C_{i+1}}{\theta_{i+1}^i} \quad \Leftrightarrow \quad C_n > C_{i+1}, \tag{D.26}$$

where C_n is the information cost of the n-th intermediary being added to the chain and C_{i+1} is the information cost of the lender of the current bottleneck (i,i+1).

Optimal intermediation emerges in a laissez-faire environment as follows. Starting from (0, I), intermediaries are added to the chain one by one, from the intermediary with the lowest information cost to the one with the highest information cost. Every time a new intermediary is added, the IC constraint $C_n > C_{i+1}$, i.e., the condition (D.27), is satisfied. And, every time when the chain is extended, the bottleneck is between the borrower 0 and the first intermediary, and recursively, as intermediaries with higher information costs are added, the bottleneck is widened. The resultant chain features intermediaries with higher information costs preceding those with lower information costs in line with the condition (13) for optimal intermediary sequencing.

Corollary D.1 (Chain formation under homogeneous θ) *Under $\theta(k) = \theta \in (0, 1)$, intermediaries are added sequentially onto the chain, starting from the one with the lowest information cost to the one with the highest information cost. After introducing the first intermediary, every new* *intermediary is inserted into the edge* (0, *1), between the borrower and the previous intermediary.*

Alternatively, the chain can start with adding the intermediary with the highest information cost, and in every subsequent step, an intermediary with the next highest information cost is added between the previous intermediary and the ultimate investor. The chain is the same as Corollary D.1: the intermediary with the highest information cost sits closest to the borrower, and along the chain, intermediaries are ranked by information costs from high to low.

Homogeneous information cost. Next, we consider the other special case where $C(k) = C$ for all k. Let (i, i+1) be the bottleneck on the existing chain of n-1 intermediaries, and consider the addition of the n-th intermediary. The condition (9) can be simplified to

$$\frac{C_n}{\theta_n^i} > \frac{C_{i+1}}{\theta_{i+1}^i} \quad \Leftrightarrow \quad \theta_n^i < \theta_{i+1}^i, \tag{D.27}$$

where θ_n^i is the conditional (on F's default) survival probability of the n-th intermediary being added to the chain and θ_{i+1}^i is the conditional survival probability of the i+1-th intermediary on the current chain. Therefore, the newly added intermediary should have smaller survival probability than the existing intermediary that will be placed after it on the extended chain.

Therefore, the chain can be formed endogenously as follows. Starting from (0, I), intermediaries are added to the chain one by one from the intermediary with the highest conditional survival probability to the one with the lowest conditional survival probability. Every time a new intermediary is added, the IC constraint $\theta_n^i < \theta_{i+1}^i$, i.e., the condition (D.27), is satisfied. And, every time when the chain is extended, the bottleneck is between the borrower 0 and the first intermediary so that, recursively, as intermediaries with lower conditional survival probabilities are added, the bottleneck is widened. The resultant chain features intermediaries with lower conditional (on the borrower 0's default) survival probability preceding those with higher conditional survival probability in line with the condition (16) for optimal intermediary sequencing.

Corollary D.2 (Chain formation under homogeneous C) *Under $C(k) = C$, intermediaries are added sequentially onto the chain, starting from the one with the highest survival probability con-*

ditional on the borrower 0's default to the one with the lowest conditional survival probability. After introducing the first intermediary, every new intermediary is inserted into the edge (0, 1).

The chain can also start with adding the intermediary with lowest conditional survival probability, and in every subsequent step, an intermediary with the next lowest information cost is added between the previous intermediary and the end lender. The chain is the same as Corollary D.2: the intermediary with the lowest conditional survival probability sits closest to the borrower, and along the chain, intermediaries are ranked by conditional survival probabilities from low to high.

Intuitively, the intermediaries with lower conditional survival probabilities should be placed closer to the borrower, because, even though the probability for collateral to reach them—the joint probability of the borrower 0's default and all preceding intermediaries' default—is higher, their survival probability is low. Such balance equalizes along the chain or smooths out the probability of each intermediary receiving the collateral (rather than passing it along to the next chain participant), in line with the general condition (10) for avoiding bottlenecks and maximizing funding capacity.