Fire Sales in a Model of Complexity

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Abstract

In this paper we present a model of fire sales and market breakdowns, and of the financial amplification mechanism that follows from them. The distinctive feature of our model is the central role played by endogenous (payoff relevant) complexity: As asset prices implode, more “banks” within the financial network become distressed, which increases each (non-distressed) bank’s likelihood of being hit by an indirect shock. As this happens, banks face an increasingly complex environment since they need to understand more and more interlinkages in making their financial decisions. This complexity brings about confusion and uncertainty, which makes relatively healthy banks, and hence potential asset buyers, reluctant to buy since they now fear becoming embroiled in a cascade they do not control or understand. The liquidity of the market quickly vanishes and a financial crisis ensues.

JEL Codes: E0, G1, D8, E5

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1 Introduction

Financial assets provide return and liquidity services to their holders. However, during severe financial crises many asset prices plummet, destroying their liquidity provision function at the worst possible time. These fire sales are at the core of the amplification mechanism and credit crunch observed in severe financial crises: Large amounts of distressed asset sales depress asset prices, which exacerbates financial distress, leading to further asset sales, and the downward spiral goes on.

There are many instances in recent financial history of these dramatic fire sales and the chaos they trigger. As explained by Treasury Secretary Paulson and Fed Chairman Bernanke to Congress in an emergency meeting soon after Lehman’s collapse, the main goal of the TARP during the subprime crisis as initially proposed was, precisely, to put a floor on the price of the assets held by financial firms in order to contain the sharp contractionary feedback loop triggered by the confusion and panic caused by Lehman’s demise. And a few years earlier, after the LTCM intervention, then Fed Chairman Greenspan wrote in his congressional testimony of October 1, 1998:

“Quickly unwinding a complicated portfolio that contains exposure to all manner of risks, such as that of LTCM, in such market conditions amounts to conducting a fire sale. The prices received in a time of stress do not reflect longer-run potential, adding to the losses incurred... ...a fire sale may be sufficiently intense and widespread that it seriously distorts markets and elevates uncertainty enough to impair the overall functioning of the economy. Sophisticated economic systems cannot thrive in such an atmosphere.”

The question arises for why apparently small shocks relative to the resources of the key agents (e.g., the subprime shock relative to the wealth of the U.S. financial system) can trigger such large fire sales and multipliers. How can these take place in deep financial markets such as those in the U.S., where a large number of potential buyers should have the resources to arbitrage the fire sales? In this paper we propose a model in which the answer to this question builds on the idea that complexity (in the common language sense of extremely complicated) becomes a central concern during crises.

The basic structure is that of a financial network that is susceptible to contagion when an unexpected event of financial distress arises somewhere in the network. During normal times, banks only need to understand the financial health of their neighbors, which they can learn at low cost. In contrast, when a significant problem arises in parts of the network
and the possibility of cascades arises, the number of nodes to be audited by each bank rises since it is possible that the shock may spread to the bank’s counterparties through their own neighbors. That is, banks become concerned that they may be hit by an indirect shock. Eventually, the problem becomes too complex for them to fully figure out, which means that banks now face significant uncertainty and they react to it by retrenching into a liquidity-conservation mode.

This structure exhibits strong interactions with secondary markets for legacy loans. Banks in distress can sell their legacy assets to meet the surprise liquidity shock. The natural buyers of the legacy assets are other banks in the financial network, which may also receive an indirect hit. When the surprise shock is small, cascades are short and buyers can inspect their neighbors to rule out an indirect hit. In this case, buyers purchase the distressed banks’ legacy assets at their “fair” prices (which reflect the fundamental value of the assets). In contrast, when the surprise shock is large, longer cascades become possible which increases the complexity of the environment, and buyers cannot rule out an indirect hit. As a precautionary measure, they hoard liquidity and turn into sellers. The price of legacy assets plummets to “fire-sale” levels, which in turn exacerbates the cascade size and credit crunch.

This feedback mechanism can generate multiple equilibria for intermediate levels of the surprise shock. When legacy assets fetch a fair price in the secondary market, the banks in distress have access to more liquidity and thus the surprise shock is contained after fewer banks are bankrupt, leading to a relatively simple environment. When the environment is simple, the natural buyers rule out an indirect hit and demand legacy assets, which ensures that these assets trade at their fair prices. Set against this benign scenario is the possibility of a fire-sale equilibrium where the price of legacy assets collapses to fire-sale levels, which leads to a longer cascade and a greater level of complexity. As the level of complexity increases, natural buyers become worried about an indirect hit and they sell their own legacy assets, which reinforces the collapse of asset prices.

This amplification mechanism is exacerbated by a complexity-externality. As a potential asset buyer chooses to pull back, the size of the potential cascade grows and with it the degree of complexity of the environment (each bank needs to explore larger segments of the network to understand the risk it is exposed to). This rise in complexity reduces the welfare of other healthy banks. It also induces these banks to pull back as a precautionary measure, which further exacerbates the fire sale and cascade.\footnote{Although we do not pursue this avenue in the paper, complexity probably plays a role in creating the incompleteness needed for a pecuniary externality to arise. If agents could sign contracts contingent on the events that follow a cascade, then the externality would be greatly reduced. However, as potential}
Our framework has two additional (and more standard) externalities. First, there is a network-liquidity externality that stems from the interlinkages of the financial system: When a bank chooses to raise external liquidity rather than to generate it from its own resources, it spreads the distress to other banks. Second, there is a fire-sale externality that arises from the negative effects that a bank’s distressed asset sales have on other banks’ balance sheets. These two externalities are present in many network and liquidity models. They interact but are distinct from the complexity externality that we highlight, which stems from the feature that any decision that lengthens the potential cascade, increases the complexity of the environments that other banks need to consider.

This paper is related to several strands of literature. In the canonical model of fire sales, these happen because during financial crises the natural buyers of the assets (other banks) also experience financial distress (cf. Shleifer and Vishny, 1992,1997). More recently, Brunnermeier and Pedersen (2008) show that when there are few players unconstrained potential buyers may choose not to arbitrage the fire sale in the short run because they anticipate a better deal in the future. Our model lies somewhere in between these two views: Most potential buyers are unconstrained, as in Brunnermeier and Pedersen (2008), but they are confused and hence fearful of going about their normal arbitrage role (and in this sense they are distressed as in Shleifer and Vishny, 1992). It is the complexity of the environment that sidelines potential buyers and exacerbates the cascade of financial bankruptcy. Importantly, this mechanism works even when the number of market participants is large.

There is an extensive literature that highlights the possibility of network failures and contagion in financial markets. An incomplete list includes Allen and Gale (2000), Lagunoff and Schreft (2000), Rochet and Tirole (1996), Freixas, Parigi and Rochet (2000), Leitner (2005), Eisenberg and Noe (2001), and Cifuentes, Ferucci and Shin (2005) (see Allen and Babus, 2008, for a recent survey). These papers focus mainly on the mechanisms by which solvency and liquidity shocks may cascade through the financial network. In contrast, we take these phenomena as the reason for the rise in the (payoff relevant) complexity of the environment in which banks make their decisions, and focus on the effect of this complexity on banks’ prudential actions. It is also worth pointing out that the complexity mechanism we emphasize in this paper is operational even for a relatively small amount of contagion. The contagion literature is sometimes criticized because it is hard to believe that many financial institutions would be caught up in a cascades lengthen, the number of contingencies that need to be written into contracts grow exponentially.
cascade of bankruptcies.\textsuperscript{2} That is, even if there is a cascade, it is reasonable to expect that it would eventually be contained (especially since banks take precautionary actions to fight the cascade). But as this paper illustrates, even \textit{partial cascades} can have large aggregate effects, since they greatly increase the complexity of the environment, and it is this complexity that is behind the destructive fire sales.\textsuperscript{3}

Our paper is also related to the literature on flight-to-quality and Knightian uncertainty in financial markets, as in Caballero and Krishnamurthy (2008), Routledge and Zin (2004), and Easley and O’Hara (2005); and to the related literature that investigates the effect of new events and innovations in financial markets, e.g., Liu, Pan, and Wang (2005), Brock and Manski (2008), and Simsek (2009). Our contribution relative to this literature is in generating the uncertainty from the complexity of the financial network itself. More broadly, this paper belongs to an extensive literature on flight-to-quality and financial crises that highlights the connection between panics and a decline in the financial system’s ability to channel resources to the real economy (see, e.g., Caballero and Kurlat, 2008, for a survey).

The organization of this paper is as follows. In Section 2 we describe the financial network and the secondary market for assets, and we introduce a surprise shock (a rare event) in the network. Section 3 we discuss a benchmark case without complexity effects (because banks can understand the network at no cost). Section 4 contains our main results. There, banks have only local knowledge about the financial network, and a sufficiently large surprise shock increases the complexity of the environment and leads to a breakdown in secondary markets. This section also highlights the dependence of the level of complexity on asset prices and demonstrates the possibility of multiple equilibria. In Section 5 we describe the three externalities in our setup and analyze their role in our main results. The paper concludes with a final remarks section and several appendices.

\textsuperscript{2}See, e.g., Brunnermeier, Crockett, Goodhart, Persaud, an Shin (2009) who argue that the \textit{domino model of financial contagion} is not useful for understanding financial contagion in a modern financial system since “.... It is only with implausibly large shocks that the simulations (of their model) generate any meaningful contagion. The reason is that the domino model paints a picture of passive financial institutions who stand by and do nothing as the sequence of defaults unfolds. In practice, however, they will take actions in reaction to unfolding events, and in anticipation of impending defaults...”

\textsuperscript{3}The role of cascades in elevating complexity was also highlighted in Haldane’s (2009) speech, who nicely captures the mechanism when he wrote that at times of stress “knowing your ultimate counterparty’s risk becomes like solving a high-dimension Sudoku puzzle.”
2 The Environment

In this section, we describe the economic environment and define equilibrium.

We consider an economy with three dates \( \{0, 1, 2\} \) in which a single good (one dollar) can be kept in liquid reserves or it can be loaned to production firms. If kept in liquid reserves, a dollar yields a dollar in the next date. Instead, if the dollar is loaned to firms, it yields \( R > 1 \) dollars at date 2. The loans are partially illiquid before date 2.

The economy has \( n \) continuums of banks denoted by \( \{b^i\}_{j=1}^n \). Each of these continuums is composed of identical banks and, for simplicity, we refer to each continuum \( b^j \) as bank \( b^j \), which is our unit of analysis.\(^4\) Each bank has initial assets which consist of \( 1 - y \) units of legacy loans, a short term debt claim on one other bank with face value \( z \) dollars, and \( y \) dollars of flexible reserves. The bank’s liabilities consist of equity and a short term debt claim with face value \( z \) dollars, held by one other bank. Until Section 5.3, we assume that short term debt cannot be rolled over and it must be paid back at date 1.

Debt is senior to equity, which implies that a bank that is unable to pay its debt at date 1 is liquidated and the proceeds are distributed to the creditors. At date 0 there is a secondary market for legacy loans and the (equilibrium) price for these loans is \( p \leq 1 \) (see below).

The central trade-off in this economy is whether the bank uses its flexible reserves to make new loans and to purchase legacy loans in the secondary market, or whether it hoards some of this liquidity (sacrificing equity value at date 2) in response to a rare event (that we describe below).

The banks’ cross debt obligations form a financial network denoted by:

\[
\mathbf{b}(\sigma) = (b^{\sigma(1)} \rightarrow b^{\sigma(2)} \rightarrow b^{\sigma(3)} \rightarrow .... \rightarrow b^{\sigma(n)} \rightarrow b^{\sigma(1)} )
\]  

where \( \sigma : \{1, .., n\} \rightarrow \{1, .., n\} \) is a permutation that assigns bank \( b^{\sigma(i)} \) to slot \( i \) in the financial network. The arc \( \rightarrow \) denotes that the bank in slot \( i \) (i.e., bank \( b^{\sigma(i)} \)) has a debt claim on the bank in the subsequent slot \( i + 1 \), and slot \( n \) has slot 1 as a forward neighbor, as illustrated in Figure 1.\(^5\)

The key ingredient of the model is that banks are uncertain about the interlinkages in the financial network. In particular, banks know the identity, \( j \), of each other bank, but

\( ^4 \)The only reason for the continuum is for banks to take other banks’ decisions as given.

\( ^5 \)In Caballero and Simsek (2009), we motivate the formation of the financial network for its role in facilitating bilateral liquidity insurance, as in Allen and Gale (2000).
they have uncertainty about the ordering of the banks, $\sigma$. Formally, we let

$$B = \{ b(\sigma) \mid \sigma : \{1, \ldots, n\} \rightarrow \{1, \ldots, n\} \text{ is a permutation} \}$$

(2)

denote the set of possible financial networks, and $B^j(\sigma) \subset B$ denote the set of financial networks which bank $b^j$ finds possible given the actual realization $b(\sigma)$. We refer to the collection $\{B^j(\sigma)\}_{j,\sigma}$ as an uncertainty model for banks.\(^6\) The no-uncertainty benchmark analyzed in the next section concerns the case in which each $B^j(\sigma)$ has the single element, $b(\sigma)$, so that banks have full knowledge of the financial network. Our main results concern the case in which banks only have local knowledge of the financial network, captured by a $B^j(\sigma)$ with multiple elements.

At date 0, the banks learn that a rare event has happened and one bank, $b^j$, will become distressed. Similar to Allen and Gale (2000), in order to remain solvent this bank needs to make $\theta$ dollars of payment (to an outsider) at date 1.

We assume that this outside debt is senior to the short term debt to the neighbor bank (it can equivalently be interpreted as a shock to the value of the bank’s assets). Consequently, these losses might spill over to other banks via the financial network and may bring them into financial distress at date 1. To prepare for date 1, at date 0 the banks take one of the following actions $A^j_0 = \{S, B\}$, which are restricted to a binary choice set

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\(^6A\) simpler alternative to the permutations is to have banks ordered in the circle in the same order as the locations (i.e. bank 1 in location 1, bank 2 in location 2, etc.) and have the uncertainty be about the identity of the bank in distress rather than about the linkages between the banks. We chose the slightly more cumbersome route of permutations because it aligns better with the idea of complexity that we want to capture here. But mechanically, the results would be very similar with the alternative formulation.
for simplicity (see Caballero and Simsek, 2009, for a related model with unrestricted action space). As a precautionary measure, the bank may choose \( A_0^j = S \), to hoard all of its flexible reserves \( y \) as liquidity and to sell all of its legacy loans \( 1 - y \) in the secondary market, keeping a completely liquid balance sheet. Alternatively, the bank may choose \( A_0^j = B \), to be a potential buyer of loans. In this case, the bank retains its own legacy loans on its balance sheet and it uses its flexible reserves either to make new loans or to buy legacy loans in the secondary market (whichever is more profitable).

Given the rare event, a bank may not be able to pay back its debt in full (despite the precautionary measures it takes), but instead it ends up paying \( q_1^j \leq z \). Similarly, the value of bank’s date 2 equity will not necessarily be \( R \), and it will be denoted by \( q_2^j \). Note that either the bank is solvent, pays \( q_1^j = z \), and its date 2 equity value is \( q_2^j \geq 0 \); or the bank is insolvent, pays \( q_1^j < z \) and its date 2 equity value is \( q_2^j = 0 \).

The bank’s preferences over its equity and debt payment are represented by the weighted average utility function:

\[
(1 - \omega^j) q_1^j + \omega^j q_2^j.
\]

The relative weight on equity, \( \omega^j \in (0, 1) \), is unrestricted and it may be bank specific. The case \( \omega^j \to 1 \) approximates a lexicographic preference of equity over debt payment.

Banks make their decisions while facing Knightian uncertainty about the network structure. In particular, bank \( b^j \) considers a range of possible financial networks, \( \mathcal{B}^j (\sigma) \), and it chooses an action that is robust to this uncertainty. Formally, let \( (q_1^j (\sigma), q_2^j (\sigma)) \) denote the bank’s equity and debt payment in equilibrium given the financial network, \( b (\sigma) \). We follow Gilboa and Schmeidler (1989)’s Maximin expected utility representation and write the bank’s optimization problem as:

\[
\max_{A_0^j (\sigma) \in \{S,B\}} \min_{b (\sigma) \in \mathcal{B}^j (\sigma) \}} u^j (\sigma).
\]

**Secondary Market for Legacy Loans**

Legacy loans are traded in a centralized exchange that opens (just) at date 0. Given the legacy loan price \( p \), the banks that choose \( A_0^j = S \) sell all of their legacy loans \( (1 - y) \) units for each bank) while the banks that choose \( A_0^j = B \) are potential buyers of legacy loans and may spend up to \( y \) (their flexible reserves).

A unit of legacy loan yields the same output, \( R \), as a new loan. Note that the price of legacy loans is bounded above by 1, which is the cost of making a new loan at date 0.
Legacy and new loans can be freely disposed of at the scrap value \( p_{\text{scrap}} \in (0, 1) \), which implies that \( p_{\text{scrap}} \) is a lower bound on prices.\(^7\) If \( p < 1 \), potential buyers spend all of their flexible reserves \( y \) on legacy loans, while if \( p = 1 \), they are indifferent between buying legacy loans and making new loans. Thus, the market clearing condition for legacy loans can be written as

\[
(1 - y) \sum_j 1 \{A^j = S\} - \frac{y}{p} \sum_j 1 \{A^j = B\} = \begin{cases} 
\geq 0 & \text{if } p = p_{\text{scrap}} \\
0 & \text{if } p \in (p_{\text{scrap}}, 1) \\
< 0 & \text{if } p = 1 
\end{cases} \quad (5)
\]

The first term on the left hand side denotes the total supply of legacy loans while the second term denotes the maximum potential demand. If the left hand side of Eq. (5) is negative for each \( p \in [p_{\text{scrap}}, 1] \), then legacy loans trade at their fair value 1, potential buyers are indifferent between buying legacy loans and making new loans, and they buy just enough legacy loans to clear the market. If the left hand side of Eq. (5) is 0 for some \( p \in [p_{\text{scrap}}, 1] \), then \( p \) is the equilibrium price. If the left hand side is positive for each \( p \in [p_{\text{scrap}}, 1] \), then there is excess supply of loans and the price is given by the scrap value, \( p_{\text{scrap}} \). We refer to the latter situation as a breakdown in the legacy loan market.

**Equilibrium**

**Definition 1.** An equilibrium is a collection of bank actions, debt payments, and equity values, \( \left[ \{A^i_0(\sigma), q^i_1(\sigma), q^i_2(\sigma)\}_j \right]_{b(\sigma)} \), and a price level \( p \in [p_{\text{scrap}}, 1] \) for legacy loans such that, given the realization of the financial network \( b(\sigma) \) and the rare event, each bank \( b^j \) chooses its actions according to the worst case financial network that it finds possible (cf. problem (4)) and the legacy loan market clears (cf. Eq. (5)).

A key aspect of the characterization of this equilibrium is the distance between each bank and the original distressed bank. Let \( i \in \{1, \ldots, n\} \) denote the slot of the distressed bank \( b^i = \sigma(i) \). Note that, for each financial network \( b(\sigma) \) and for each bank \( b^j \), there exists a unique \( k \in \{0, \ldots, n-1\} \) such that

\[ j = \sigma(i - k) \]

which we define as the distance of bank \( b^j \) from the distressed bank.\(^8\) The distance \( k \) is the payoff relevant information for a bank \( b^j \).

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\(^7\)The scrap value could represent the value of the asset to an investor outside the banking sector.

\(^8\)We use modulo \( n \) arithmetic for the slot index \( i \), e.g. \( i - k = -1 \) represents the slot \( n - 1 \).
3 A Benchmark Equilibrium without Complexity

In this section, we characterize the equilibrium for a benchmark case in which banks have full knowledge of the interlinkages between all the banks in the financial network. Formally, we consider the uncertainty model given by $\mathcal{B}^j (\sigma) = \{b(\sigma)\}$ for each $j$ and $\sigma$. In this no-uncertainty benchmark we show that if the network is deep (i.e., there is a large number of banks) secondary markets do not break down and the financial network is resilient to a perturbation. That is, the size of financial cascades is contained and aggregate loan contraction is limited. These relatively benign results contrast with those we obtain in the next section once we introduce complexity.

We characterize the equilibrium in two steps: We start by describing the banks’ actions and payoffs for a given price level of legacy loans, $p$; and then solve for the equilibrium price using the legacy loan market clearing condition (5). Suppose the loan prices are fixed at some $p \in [p_{\text{scrap}}, 1]$. First consider banks’ optimal actions, taking the banks’ cross debt payments, $\{q^j_i\}_j$, as given. The date 1 liquidity need of a bank $b^{\sigma(i-k)}$ with distance $k$ is given by:

$$z - q^\sigma(i-(k-1)) + \theta [k = 0]$$  \hspace{1cm} (6)

(where $\theta [\cdot]$ denotes the product of $\theta$ and the indicator function). The first term captures the payment the bank needs to make on its short term debt. The second term captures the equilibrium payment the bank receives from its forward neighbor. The last term captures the additional payment that the original distressed bank needs to make.

We refer to any bank with a positive liquidity need (6), as a distressed bank. If a distressed bank is unable to meet the liquidity need, then it is insolvent and it is liquidated at date 1. At date 0, the bank can choose the precautionary action, $A^j_0 = S$, which enables it to obtain $l(p) = y + (1 - y) p$ dollars of additional liquidity at date 1. If $l(p)$ is greater than the liquidity need in (6), then the bank is able to avert insolvency by choosing $A^j_0 = S$. Otherwise, the bank is insolvent even if it takes the precautionary action $A^j_0 = S$, which it takes nonetheless since this increases its debt payment at date 1. In contrast, a non-distressed bank (for which the liquidity need in (6) is zero) is able to pay its debt back in full. Hence, this bank chooses the aggressive action, $A^j_0 = B$, to maximize its equity value. This analysis establishes that a bank (with the preference (3)) chooses the precautionary action, $A^j_0 = S$, if and
only if it is distressed (in the sense of having a positive liquidity need).

Consider next banks’ debt payments and equity values, \( \{q_1^j, q_2^j\}_j \). We conjecture that, under appropriate parametric conditions, there exists a threshold \( K(p) \in \{1, \ldots, n-1\} \), which depends on loan prices, such that all banks with distance \( k \leq K(p) - 1 \) are insolvent (there are \( K(p) \) such banks) while the banks with distance \( k \geq K(p) \) remain solvent. That is, the crisis will partially cascade through the network but will be contained after \( K(p) \leq n-1 \) banks have failed. We refer to \( K(p) \) as the cascade size.

Under our conjecture, the original distressed bank, \( b^{(i)} \), receives full payment from its debt claims on its forward neighbor, i.e., \( q_1^{(i+1)} = z \). Hence, the liquidity need of bank \( b^{(i)} \) is \( \theta > 0 \). This bank chooses the precautionary action, \( A_0^i = S \). If \( \theta \leq l(p) \), then the bank avoids insolvency and the cascade size is \( K(p) = 0 \).

If instead \( \theta > l(p) \), then bank \( b^{(i)} \) is insolvent. The bank will pay

\[
q_1^{(i)} = z + l(p) - \theta < z, \tag{8}
\]

where we assume \( z + l(p) - \theta \geq 0 \) to simplify the expressions.\(^9\) Note that bank \( b^{(i)} \) will receive \( z \) units from its debt claims on the forward neighbor bank \( b^{(i+1)} \), it will have \( l(p) \) units of liquidity at date 1, and it has to make a payment \( \theta \).

In this case, the neighbor bank \( b^{(i-1)} \) with distance 1 from the distressed bank receives \( q_1^{(i)} < z \) from its debt claims. Hence, its liquidity need, \( (6) \), is given by

\[
z - q_1^{(i)} = \theta - l(p). \tag{9}
\]

where the second expression comes from using \( (8) \) to substitute for \( q_1^{(i)} \). Since we are considering the case \( \theta > l(p) \), the neighbor bank also has a positive liquidity need, and thus it chooses \( A_0^{(i-1)} = S \). If \( \theta \leq 2l(p) \), then the neighbor bank’s own \( l(p) \) is greater than its liquidity need. In this case, this bank is able to avoid insolvency, and the cascade size is \( K(p) = 1 \). Otherwise, the neighbor bank is also insolvent, and it will pay

\[
q_1^{(i-1)} = l(p) + q_1^{(i)}. \tag{10}
\]

From this point onwards, a pattern emerges. The payment by an insolvent bank

\(^9\)If this condition is violated, then the original distressed bank is unable to make the outside payment, and it pays zero on its short term debt. Hence, this condition can be relaxed simply by modifying \( (8) \) to

\[
q_1^{(i)} = \max(0, z + l(p) - \theta).
\]

The rest of the analysis is identical. We assume this condition because it simplifies the expressions by eliminating the max operator.
$b^{\sigma(i-(k-1))}$ (with distance $k - 1$) is given by

$$q_1^{\sigma(i-(k-1))} = l(p) + q_1^{\sigma(i-(k-2))} = l(p)(k - 1) + q_1^{\sigma(i)}.$$

Here, the first equality shows that banks’ payments are linearly increasing in their distance, and the second equality uses this property to solve for the payment of bank $b^{\sigma(i-(k-1))}$ in closed form. Using this expression along with Eq. (9), bank $b^{\sigma(i-k)}$ (with distance $k$) has the liquidity need:

$$z - q_1^{\sigma(i-(k-1))} = \theta - l(p)k.$$

That is, banks’ liquidity needs are linearly decreasing in its distance, $k$. If $\theta > l(p)k$, then bank $b^{\sigma(i-k)}$’s liquidity need is positive, and thus it chooses the precautionary action, $A_0^{\sigma(i-k)} = S$. If $\theta \leq l(p)(k + 1)$, then this bank is able to avoid insolvency. Otherwise, this bank will also be insolvent despite taking the precautionary action.

In view of these observations, let $K(p)$ denote the first nonnegative integer such that $\theta \leq l(p)(K(p) + 1)$. When the number of banks is sufficiently large, i.e., when $n \geq K(p) + 1$, then all banks $b^{\sigma(i-k)}$ with distance $k \in \{0, 1, \ldots, K(p) - 1\}$ are insolvent since their liquidity needs are greater than their $l(p)$. These banks choose $A_0^j = S$ to improve their liquidation outcome. In contrast, bank $b^{\sigma(i-K(p))}$ is solvent, since it can meet its losses by choosing the precautionary action, $A_0^{\sigma(i-K(p))} = S$. Since bank $b^{\sigma(i-K(p))}$ is solvent, all banks $b^{\sigma(i-k)}$ with distance $k \in \{K(p) + 1, \ldots, n - 1\}$ are also solvent since they do not incur losses in cross debt claims. These banks are potential buyers of legacy loans, i.e., they choose $A_0^j = B$. This verifies our conjecture for a partial cascade of size $K(p)$ under the parametric conditions stated above. For future reference, we strengthen the parametric conditions to

$$\theta < z + l(p_{\text{scrap}}) \quad \text{and} \quad n \geq K(1) + 1,$$

so that there exists a partial cascade for any $p \in [p_{\text{scrap}}, 1]$. Figure 2 illustrates the partial cascade.

From the above analysis, the cascade size $K(p)$ can also be solved in closed form as

$$K(p) = \left[ \frac{\theta}{l(p)} \right] - 1 = \left[ \frac{\theta}{y + (1-y)p} \right] - 1,$$

where $[x]$ denotes the ceiling function (i.e., the unique integer such that $[x] - 1 < x \leq [x]$), and the second equality substitutes the definition of $l(p)$ from (7). This expres-
Figure 2: The partial cascade in the no-uncertainty benchmark.

The assertion shows that $K(p)$ is decreasing in $p$: with a higher loan price, $l(p)$ of each bank is greater, thus the crisis is contained after a smaller number of insolvencies. The negative dependence of the cascade size on the price of loans plays an important role in the next section in which we consider the equilibrium with endogenous complexity. Note also that $K(p)$ is weakly decreasing in $y$: if banks’ initial balance sheets have more liquid reserves, then their $l(p)$ is greater, which shortens the cascade. The next lemma summarizes this discussion.

**Lemma 1.** Suppose banks know the financial network (i.e., $B_j(\sigma) = \{b(\sigma)\}$ for each $j$ and $\sigma$), that the loan prices are exogenously fixed at $p \in [p_{\text{scrap}}, 1]$, and that condition (11) is satisfied. Then, there exists a partial cascade of size $K(p)$, where $K(p)$ is defined by (12). Banks with distance from the distressed bank $k \leq K(p) - 1$ are insolvent and they choose $A_0^j = S$. The transition bank with distance $K(p)$ averts insolvency by choosing $A_0^j = S$. The remaining banks with distance $k \geq K(p) + 1$ are solvent and they choose $A_0 = B$.

We next consider the legacy loan market clearing condition and solve for the equilibrium level of prices. We claim that if $n$ is sufficiently large, the endogenous loan price in the no-uncertainty benchmark is the maximum price $p = 1$.

To see this, note that the insolvent banks (there are $K(p)$ of them) and the transition bank (at distance $K(p)$) choose $A_0^j = B$ and sell all of their existing loans. Hence, the aggregate supply of loans is $(K(p) + 1) (1 - y)$. The remaining solvent banks \( \{b^{(i-k)}\}_{k=K(p)+1}^{n-1} \) (there are $n - K(p) - 1$ of them) choose $A_0^j = B$, i.e., they are potential
buyers of loans. Suppose \( n \) is sufficiently large so that

\[
(n - K (p) - 1) y > p (1 - y) (K (p) + 1) \text{ for all } p \in [p_{\text{scrap}}, 1].
\]  

(13)

Under this condition, the demand from the potential buyers exceed the supply of loans for any price level \( p < 1 \), thus the loan market clearing condition (5) implies that \( p = 1 \).

Intuitively, if the cascade is only partial and banks know the financial network, then there exist safe banks which will not make losses from cross-debt claims and know that much. These banks do not sell loans and are ready to use their flexible reserves to purchase loans from distressed banks. When there are sufficiently many banks, the demand from these safe banks is enough to absorb the supply from the distressed banks, ensuring that the secondary loans are traded at their fair price 1. We refer to condition (13) as the deep secondary market assumption. The next proposition summarizes the above discussion and characterizes the symmetric equilibrium for the no-uncertainty benchmark.

**Proposition 1.** Suppose banks know the financial network, and that condition (11) and the deep secondary market assumption (13) hold. Then,

(i) The unique equilibrium price is \( p = 1 \) (no fire sales).

(ii) At date 1, the banks with distance \( k \leq K (1) - 1 \) are insolvent, while the banks with distance \( k \geq K (1) \) are solvent.

(iii) At date 0, the insolvent banks and the transition bank with distance \( K (1) \) choose \( A_0 = S \). These banks sell all of their loans in the secondary market. The safe banks with distance \( k \geq K (1) + 1 \) choose \( A_0 = B \). These banks are indifferent between buying legacy loans and making new loans. They spend a portion of their flexible reserves to buy the legacy loans sold by the insolvent banks and they make new loans with the rest of their reserves. The aggregate level of new loans made in this economy is given by:

\[
\mathcal{Y} = (n - K (1) - 1) y - (K (1) + 1) (1 - y)
\]

\[
= ny - \lfloor \theta \rfloor.
\]  

(14)

**Discussion.** Figure 3 displays the equilibrium in the benchmark economy for particular parameterization of the model. The figure demonstrates that the loan prices are fixed at 1, the cascade size is increasing and the aggregate level of new loans is decreasing with respect to \( \theta \). Intuitively, as \( \theta \) increases, there are more losses to be contained, which further spreads the insolvency. As the insolvency spreads, more banks hoard their flexible reserves as liquidity or use these reserves to purchase legacy loans form distressed banks instead of making new loans, which lowers \( \mathcal{Y} \). Note, however, that \( \mathcal{Y} \) decreases “smoothly”
with $\theta$. These results offer a benchmark for the next section. There we show that once auditing becomes costly, both $K$ and $Y$ may experience large changes with small increases in $\theta$.

4 Endogenous Complexity and Fire Sales

We now introduce our key assumption: Banks only have local knowledge about the financial network $b(\sigma)$. As we will see, in this context when the shock is small, the system behaves exactly as in the benchmark. But when the shock is large, banks need to understand distant (complex) linkages in order to assess the amount of counterparty risk they are facing. Their inability to figure out these complex linkages triggers a set of precautionary actions which overturns the relatively benign implications of the benchmark environment.

By local knowledge we mean that each bank observes its forward neighbor but is otherwise uncertain about how the remaining banks are allocated to the remaining financial slots (cf. Eq. (1)). Formally, we consider the uncertainty model given by:

$$B^j(\sigma) = \left\{ b(\tilde{\sigma}) \in B \left| \begin{array}{l} \tilde{\sigma}(i) = \sigma(i) \\ \tilde{\sigma}(i + 1) = \sigma(i + 1) \end{array} \right. \right\}, \text{ where } i = \sigma^{-1}(j) \tag{15}$$

for each $j$ and $\sigma$. Note that the bank knows its own slot and the slots of its forward neighbor, but it is otherwise uncertain about how the other banks are assigned to the
remaining slots. This assumption implies that banks with distance \( k \leq 1 \) know their distances from the distressed bank, while banks with distance \( k \geq 2 \) are uncertain about their distances and they find possible all distances \( \tilde{k} \in \{2, 3, \ldots, n - 1\} \).

Let us now repeat the steps of the previous section. Suppose the loan prices are fixed at some \( p \in [p_{\text{scrap}}, 1] \), and consider banks’ optimal actions, taking the cross debt payments, \( \{q_i^j\}_j \), as given. Note that a sufficient statistic for bank \( b^j \) with distance \( k \) to choose action \( A_0^j \in \{S, B\} \) is the amount it will receive in equilibrium from its forward neighbor. In particular, to decide on the level of its precautionary measure, this bank only needs to know its liquidity need in (6), which only depends on the debt payment of its forward neighbor. Formally, if the bank chooses \( A_0^j \) at date 0 and its forward neighbor pays \( x \) at date 1, then this bank’s debt payment and equity value can be written as a function \( (q_1 [A_0^j, x], q_2 [A_0^j, x]) \). However, the bank chooses \( A_0^j \) while facing uncertainty about the financial network, and consequently about \( x = q_1^{(i-(k-1))} (\sigma) \). More specifically, the bank knows that \( x \) lies in the interval:

\[
\begin{align*}
\left[ x_{\text{worst}} = \min_{b(\tilde{\sigma}) \in B(\sigma)} q_1^{(i-(k-1))} (\tilde{\sigma}), \quad x_{\text{best}} = \max_{b(\tilde{\sigma}) \in B(\sigma)} q_1^{(i-(k-1))} (\tilde{\sigma}) \right],
\end{align*}
\]

but it is uncertain about the exact location of \( x \) in this interval.

For future reference, we define \( x_{\text{best}} - x_{\text{worst}} \) as the payoff relevant complexity faced by the bank. Intuitively, this is a measure of payoff uncertainty generated by the complexity of the financial network. Note that the complexity of the network generates a fixed and exogenous amount of uncertainty for the bank, as captured by the uncertainty model \( \{B^j (\sigma)\}_{j, \sigma} \). However, the effect of this uncertainty on the bank’s payoff is endogenous, as captured by the payoff relevant complexity. Some economic environment elevate the payoff relevant complexity and trigger a set of precautionary actions, as we will shortly see.

To characterize the bank’s optimal action, note that \( q_1 [A_0^j, x] \) and \( q_2 [A_0^j, x] \) are weakly increasing in \( x \) for any choice of action. That is, the bank’s debt and equity payments are increasing in the amount it receives from its forward neighbor regardless of the ex-ante precautionary measure it takes. Thus, since the bank is facing Knightian uncertainty (cf. problem (4)), it will choose its precautionary action as if it will receive from its forward neighbor the lowest possible payment \( x_{\text{worst}} \).

It remains to characterize the lowest possible payment, \( x_{\text{worst}} \). To this end, we define a useful notion of equilibrium. We say that the equilibrium allocation is distance based and monotonic if the banks’ equilibrium payments can be written as an increasing function of their distance from the distressed bank. That is, there exists weakly increasing payment
and value functions $Q_1, Q_2 : \{0, \ldots, n-1\} \to \mathbb{R}$ such that

$$
\left(q_1^{\sigma(i-k)}(\sigma), q_2^{\sigma(i-k)}(\sigma) \right) = (Q_1[k], Q_2[k])
$$

for all $b(\sigma)$ and $k$. We conjecture (and verify in Appendix A.1) that the equilibrium is distance based and monotonic.

Under this conjecture, the payment of the bank’s forward neighbor can be written as $x = Q_1[k-1]$. Then, the bank’s uncertainty about the forward neighbor’s payment $x = Q_1[k-1]$ reduces to its uncertainty about the forward neighbor’s distance $k-1$, which is equal to one less than its own distance $k$. If the bank knows its distance to the distressed bank, i.e., if $k \in \{0, 1\}$, then it chooses its optimal action $A_0^i \in \{S, B\}$ knowing that it will receive $x = Q_1[k-1]$ from its forward neighbor. On the other hand, if the bank is uncertain about its distance, i.e., if $k \geq 2$, then it assigns a positive probability to all distances $\tilde{k} \in \{2, \ldots, n-1\}$. Moreover, since $Q_1[\cdot]$ is an increasing function, the payment $Q_1[k-1]$ is minimal for the distance $\tilde{k} = 2$. Hence a bank $b^i$ with distance $k \geq 2$ chooses $A_0^i \in \{S, B\}$ as if it will receive $x_{\text{worst}} = Q_1[1]$ from its forward neighbor.

In words, the banks that are uncertain about their distances to the distressed bank choose their precautionary action as if they are closer to the distressed bank than they actually are.

Formally, our next lemma establishes that all banks with distance $k \geq 2$ choose the action that the bank with distance $\tilde{k} = 2$ would choose if the information was freely available (characterized in Lemma 1). If the no-uncertainty cascade size is given by $K(p) \geq 2$, so that the bank with distance $\tilde{k} = 2$ would take the precautionary action $A_0^i = S$, then all banks with $k \geq 2$ also take the precautionary action $A_0^i = S$ and lead to a collapse in new loans, as illustrated in Figure 4. The proof of the following lemma is relegated to Appendix A.1 since the intuition is provided by the above discussion.

**Lemma 2.** Consider the setup of Lemma 1, but now information is costly rather than free, so that banks know only their forward neighbor and they are otherwise uncertain about the financial network $b(\sigma)$. Then the equilibrium is distance based and monotonic, and the cascade size is the same as in the no-uncertainty economy. However, banks’ date 0 actions, debt payments, and equity values are potentially different.

Each bank $b^i$ with distance $k \in \{0, 1\}$ chooses the same action that it would choose in the no-uncertainty economy (characterized in Lemma 1). Each bank $b^i$ with distance $k \in \{2, \ldots, n-1\}$ chooses the same action that the bank with distance 2 would choose in the no-uncertainty economy. In particular, there are two cases to consider, depending on the cascade size:
Figure 4: The partial cascade and the precautionary actions with network uncertainty. The top panel displays the case $K(p) \leq 1$. The bottom panel displays the case $K(p) \geq 2$. 
If $K(p) \leq 1$, then the crisis in the no-uncertainty economy would not cascade to bank with distance $1$, which would choose $A^i_0 = B$. Thus, each bank $b^i$ with distance $k \in \{2, \ldots, n - 1\}$ chooses $A^i_0 = B$, and the equilibrium actions and payments are identical to the no-uncertainty economy described in Lemma 1.

If $K(p) \geq 2$, then the crisis in the no-uncertainty economy would cascade to the bank with distance $2$, which would choose the precautionary action, $A^i_0 = S$. Thus, each bank $b^i$ with distance $k \in \{2, \ldots, n - 1\}$ chooses $A^i_0 = S$.

Note that the loan trade decisions of the banks with distance $k \geq 2$ depend on the no-uncertainty cascade size $K(p)$. In particular, if $K(p) \leq 1$, these banks are potential buyers in the loan market, while if $K(p) \geq 2$, they are sellers. This dependence of the banks’ loan trades on the no-uncertainty cascade size $K(p)$ (which itself depends on the loan price) plays a key role in subsequent analysis, where we endogenize the loan prices and complete the characterization of the equilibrium.

We next solve the equilibrium level of loan prices in the costly information setting and present our main results. There are three cases to consider depending on the cascade size $K(p)$ over the price range $p \in [p_{\text{scrap}}, 1]$.

**Case (i).** If $K(p_{\text{scrap}}) \leq 1$, then we conjecture that there is a unique symmetric equilibrium, that we refer to as the *fair-price equilibrium*, in which loan markets endogenously clear and loans trade at their fair price $p = 1$. To verify this conjecture, recall that $K(p)$ is a decreasing function so that $K(p) \leq K(p_{\text{scrap}}) \leq 1$ for all $p \in [p_{\text{scrap}}, 1]$. Hence, regardless of the endogenous price $p$, Lemma 2 implies that all banks with $k \geq 2$ choose $A^i_0 = B$, and as such, these banks are potential buyers of loans. Thus, under the deep secondary market assumption (13), the unique equilibrium price is $p = 1$. Once the equilibrium price is determined, the remaining equilibrium allocations are uniquely determined as described in Lemma 2, proving our conjecture for this case.

**Case (ii).** If $K(1) \geq 2$, we conjecture that there is a unique symmetric equilibrium, which we refer to as the *fire-sale equilibrium*, in which there is a breakdown in the loan market and $p = p_{\text{scrap}}$. To see this, note that $2 \leq K(1) \leq K(p)$ for all $p \in [p_{\text{scrap}}, 1]$, thus Lemma 2 implies that all banks with $k \geq 2$ choose $A^i_0 = S$. In words, these banks are also sellers in the loan market. Thus, the legacy loan market features $n$ sellers and no buyers. The market clearing condition (5) implies that $p = p_{\text{scrap}}$ (i.e., there is a breakdown in the secondary loan market).
Case (iii). If \( K(1) \leq 1 < 2 \leq K(p_{\text{scrap}}) \), we conjecture that there are two stable equilibria: one fair-price equilibrium and one fire-sale equilibrium. To see this, first suppose that the price of loans is given by \( p = 1 \) so that the cascade size satisfies \( K(p) \leq 1 \). Then, the analysis for case (i) applies unchanged. In particular, all banks with distance \( k \geq 2 \) are potential buyers and the price 1 clears the market, verifying that there is a fair-price equilibrium. Next suppose that the price of loans is given by \( p = p_{\text{scrap}} \) so that the cascade size satisfies \( K(p_{\text{scrap}}) \geq 2 \). Then, the analysis for case (ii) applies unchanged. All banks with distance \( k \geq 2 \) are sellers, and loan prices collapse to \( p = p_{\text{scrap}} \), verifying that there is a fire-sale equilibrium.

We summarize these results in the following, and main, proposition.

**Proposition 2.** Consider the setup of Proposition 1 except that banks only have local understanding of the network, so that banks know only their forward neighbor and they are otherwise uncertain about the financial network \( b(\sigma) \). Let \( K(p) \) denote the cascade size in the no-uncertainty economy with price level \( p \in [p_{\text{scrap}}, 1] \), defined by (12).

(i) Unique fair-price equilibrium: If \( K(p_{\text{scrap}}) \leq 1 \), there is a unique equilibrium in which loans trade at their fair price \( p = 1 \). The banks with distance \( k \leq K(1) \) choose \( A_0^j = S \) and sell their loans, while the safe banks with distance \( k \geq K(1) + 1 \) choose \( A_0^j = B \) and are indifferent between using their reserves to make new loans or to buy legacy loans in the secondary market. The aggregate level of new loans is equal to the benchmark Eq. (14).

(ii) Unique fire sale equilibrium: If \( K(1) \geq 2 \), then there is a unique equilibrium in which there is a breakdown in the secondary loan market, i.e., there is an excess supply of loans and \( p = p_{\text{scrap}} \). All banks choose \( A_0^j = S \) and sell their loans and hoard their liquid reserves. In this case, there are no new loans, \( \mathcal{V} = 0 \).

(iii) Multiple equilibria: If \( K(1) \leq 1 < 2 \leq K(p_{\text{scrap}}) \), there are two stable equilibria.

In the fair-price equilibrium, loans trade at their fair price \( p = 1 \), the safe banks are indifferent between making new loans or purchasing loans in the secondary market, and the aggregate level of new loans \( \mathcal{V} \) is given by the benchmark Eq. (14).

In the fire sale equilibrium, \( p = p_{\text{scrap}} \), all banks dump their legacy loans in the secondary market, and there are no new loans, \( \mathcal{V} = 0 \).

**Discussion.** Figure 5 displays the equilibria with network uncertainty for a particular parameterization of the model. The top panel reproduces the cascade size \( K(p) \) in the no-uncertainty benchmark as a function of the losses in the originating bank \( \theta \), when loan prices are fixed at \( p = p_{\text{scrap}} \) and \( p = 1 \). The second panel plots the payoff relevant
Figure 5: **Equilibria with network uncertainty.** The top panel plots the cascade size, \( K(p) \), in the no-uncertainty benchmark as a function of the losses in the originating bank \( \theta \), when the loan price is fixed at respectively \( p = p_{\text{scrap}} \) and \( p = 1 \). The second panel plots the payoff relevant complexity, \( x_{\text{best}} - x_{\text{worst}} \), faced by (safe) banks with distance \( k \geq K(p) + 1 \). The remaining two panels display the equilibria with network uncertainty. They respectively plot the loan price and the aggregate level of new loans as a function of \( \theta \), for both the fair-price and the fire-sale equilibria.
complexity, $x^{best} - x^{worst}$ [cf. Eq. (16)], faced by banks with distance $k \geq K(p) + 1$. These banks are safe in the sense that they do not make any losses from cross debt claims, but they do not necessarily know that much because of their uncertainty about the financial network. The remaining two panels display the equilibria with network uncertainty, illustrating the characterization in Proposition 2. Note that there is a unique equilibrium for small and large levels of $\theta$, but there are multiple equilibria for intermediate levels of $\theta$.

When $\theta$ is sufficiently small so that $K(p_{\text{scrap}}) \leq 1$ (i.e., when the no-uncertainty benchmark features a short cascade even for the price level $p = p_{\text{scrap}}$) there is a unique fair price equilibrium. In this equilibrium, the safe banks are able to rule out an indirect hit, which leads to a low level of (namely, zero) payoff relevant complexity for these banks. Consequently, these banks use their reserves to make new loans and to demand assets. The aggregate level of new loans is the same as in the no-uncertainty benchmark, and assets trade at their fair prices.

In contrast, when $\theta$ is sufficiently large so that $K(1) \geq 2$ (i.e., when the cascade size in the no-uncertainty benchmark is sufficiently large) there is a unique fire-sale equilibrium. In this equilibrium, the aggregate level of new loans makes a very large and discontinuous drop to zero. In particular, when the losses (measuring the severity of the initial shock) are beyond a threshold, the cascade size becomes so large that the safe banks are unable to tell whether they are connected to the distressed bank or not. In this case, these banks face a significant payoff relevant complexity. They respond to this complexity by acting as if they are closer to the distressed bank than they actually are, hoarding much more liquidity than in the no-uncertainty benchmark and leading to a severe credit crunch episode. Moreover, these banks, who would be potential buyers of loans in the no-uncertainty benchmark, become sellers and this leads to a collapse in asset prices, which further exacerbates the cascade. This result provides a rationale for the collapse of asset prices in an environment in which complexity suddenly (and endogenously) rises.

When $\theta$ is in an intermediate range, the cascade size is manageable if price of loans is high (i.e., $K(1) \leq 1$), however it becomes unmanageable if loans trade at the fire-sale price (i.e., $K(p_{\text{scrap}}) \geq 2$). In this case, the interaction between asset prices and the endogenous level of (payoff relevant) complexity generates multiple equilibria.

In the fair-price equilibrium, loans trade at a higher price and the cascade size is relatively small, which reduces the payoff relevant complexity faced by the safe banks. With the lower level of complexity, these banks become potential buyers of loans, which ensures that loans trade at the higher price and that the cascade is shorter.

Set against this benign scenario is the possibility of a fire-sale equilibrium, in which
the price of loans collapses and there is a longer cascade, which increases the level of payoff relevant complexity faced by the safe banks. As the level of complexity increases, these banks panic and sell their loans, which reinforces the collapse of loan prices.

Note also that, whenever there are multiple equilibria, the fair-price equilibrium Pareto dominates the fire-sale equilibrium for all banks. Intuitively, the fire-sale equilibrium entails two distinct social costs: fewer new loans are made and banks are worse off because of the greater payoff relevant complexity. In the next sections, we identify the negative externalities in our setup that account for these social costs.

5 Externalities

In this section we discuss the various externalities present in our setup and we highlight the role they play in our main results. Our model features a novel complexity externality which emerges from the endogeneity of the payoff relevant complexity faced by banks. In addition, the model has two (more standard) externalities: the fire-sale externality, which stems from the interaction of loan prices and liquidity constraints, and the network-liquidity externality, which emerges directly from the interlinkages between banks.

5.1 Complexity Externality

In our model, any action that increases the length of the cascade increases the payoff relevant complexity faced by banks that are uncertain about their distance from the distressed bank. Since banks are averse to complexity (which we model as Knightian uncertainty), an increase in complexity leads to a welfare reduction for these banks. Hence, actions that increase the cascade size impose a negative externality, which we call the complexity externality.

To formalize this point, consider the setup of Lemma 2, that is, suppose that the loan prices are exogenously fixed (which shuts down the fire-sale externality) and that banks have only local knowledge of the financial network. To isolate the complexity externality, consider also a slight extension of the model in which a bank outside the financial network can decrease the cascade size by taking a costly action at date 0. Formally, denote the action by $A_{0}^{\text{outside}} \in \{0, 1\}$, and suppose that $A_{0}^{\text{outside}} = 1$ reduces the initial losses from $\theta$ to some $\tilde{\theta}$, which leads to a shorter cascade.\textsuperscript{10} Let $K(p, A_{0}^{\text{outside}})$ denote the cascade size in

\textsuperscript{10}In reality, one can imagine a number of ways in which an outside bank, or an outside government, could shorten the cascade size at some private cost. For example, the bank could bail out one of the distressed banks, or it could provide additional liquidity to support loan prices.
the extended model and consider a parameterization such that $K(p, 1) \leq 1 < 2 = K(p, 0)$. That is, the cascade size without the outside action is above the critical threshold of 1, and the outside action is able to reduce the cascade size to a level below the critical threshold.

Our goal is to characterize the effect of action $A_{0, \text{outside}}$ on banks that are uncertain about their distance from the distressed bank (i.e., banks with distance $k \geq 2$). First consider the case in which the outside action is taken, $A_{0, \text{outside}} = 1$. In this case, the cascade is sufficiently short that these banks are able to rule out an indirect hit: They face zero payoff relevant complexity, they choose $A_{i} = B$, and their equity value is given by $q_{2} = R$. In contrast, if $A_{0, \text{outside}} = 0$ and the cascade is longer, then the banks with distance $k \geq 2$ are worried that they might suffer an indirect hit: They face significant payoff relevant complexity, which greatly lowers their welfare. They respond to this complexity by choosing $A_{i} = S$, which lowers their equity value to $q_{2} < R$.

Hence, if the outside bank chooses $A_{0, \text{outside}} = 0$, then it exerts a negative complexity externality on a large number of banks. In equilibrium, the costly action is not taken, i.e., $A_{0, \text{outside}} = 0$, regardless of the cost of action and regardless of the number of banks that benefit from the action. This is because the outside bank does not internalize the benefits from reduced complexity.

While this example is useful to illustrate the complexity externality, note that the externality is also present in our main model without the outside bank, that is, banks within the network also impose complexity externalities on each other. In this case, the complexity externality is pecuniary because it operates through the interaction of loan prices and the cascade size. In particular, a bank that decides to sell loans (i.e., that chooses the precautionary action, $A_{i} = S$) has a (small) negative impact on loan prices. This in turn has a (small) positive impact on the cascade size: with a lower loan price, the $l(p)$ of each bank is greater, thus the crisis is contained after a smaller number of insolvencies (cf. Eq. (12)). This increases the payoff relevant complexity faced by other banks and lowers their welfare, demonstrating the complexity externality.

The complexity externality may also lead to multiple Pareto-ranked equilibria in our setup, as we have already seen in Proposition 2. In particular, an increase in payoff relevant complexity due to a reduction in the loan price not only lowers the welfare of many banks, but also induces these banks to take extreme precautionary measures, which includes further asset sales. The sale of assets by banks in panic mode reduces asset prices further, which leads to a vicious cycle culminating in the fire-sale equilibrium. In contrast, an increase in asset prices reduces the payoff relevant complexity, which may mitigate the precautionary measures and turn more sellers into buyers, leading to a virtuous spiral towards the fair price equilibrium.
5.2 Fire-sale Externality

Consider a bank that decides to sell some loans, leading to a small decline in loan prices. This action has a small positive effect on the net budgets of the banks that buy legacy loans, while it has a small negative effect on the net budgets of the banks that sell legacy loans. Absent further effects, the welfare impacts of these budget changes would typically “net out,” which is the content of the first welfare theorem. However, in our setup, a fraction of the banks (those with distance $k \leq K(p)$) also face binding liquidity constraints. A small decline of asset prices also decreases the $l(p)$ of these banks and tightens their liquidity constraints, leading to a further reduction in their welfare. Consequently, the effects of price changes do not necessarily “net out,” and loan prices feature a negative pecuniary externality which we call the fire-sale externality.

To formalize this point, let us consider the benchmark economy analyzed in Section 3. This setting shuts down the complexity externality (since the banks know the financial network). Since the cascade size $K(p)$ is decreasing in $p$, there exists some $\bar{p} \in [p_{\text{scrap}}, 1]$ such that, for any $\varepsilon > 0$ we have

$$K(\bar{p} - \varepsilon/2) = K(\bar{p} + \varepsilon/2) + 1.$$ 

That is, the cascade size increases by one in response to an arbitrarily small decrease in loan prices. The small price drop from $\bar{p} + \varepsilon/2$ to $\bar{p} - \varepsilon/2$ leads to the insolvency of one more bank, inflicting a discrete negative effect on the welfare of this bank, while it has a continuous effect on the welfare of other banks. Hence, for sufficiently small $\varepsilon$, the net welfare effect of the price change from $\bar{p} + \varepsilon/2$ to $\bar{p} - \varepsilon/2$ is negative, demonstrating the fire-sale externality.

Note also that the complexity externality analyzed in the previous section is more potent than the fire-sale externality. The reason is that the fire-sale externality affects banks that face binding liquidity constraints. In contrast, the complexity externality affects all banks that are uncertain about the financial network, which, in practice, includes virtually all financial institutions. The greater scope of the complexity externality also leads to widespread (precautionary) actions, which has the potential to create aggregate effects, price changes, and multiple equilibria.\footnote{Moreover, in our model there is a clear hierarchy. Recall that in the model without complexity there is no fire sale in equilibrium, and hence there is no fire-sale externality. Thus, it is (payoff relevant) complexity that creates the opportunity for a fire-sale equilibrium.}
5.3 Network-liquidity Externality

The network-liquidity externality emerges from the banks’ interlinkages and their localized actions that directly affect their neighbors. Thus far, we have simplified the model by abstracting away from these localized actions. In particular, we have assumed that all short term debt claims must be settled at date 1. However, a bank could choose to roll-over its debt claim on its neighbor to date 2, which would relax its neighbor’s liquidity constraint and which could potentially lead to a shorter cascade. In this section, we consider the extension of the model with banks’ (localized) roll-over actions, and we show that the equilibrium is unchanged. Put differently, all banks choose to withdraw their debt claims immediately. In essence, banks do not take into account the effect of their actions on their neighbors’ liquidity constraints, thus inflicting a negative externality which we call the network-liquidity externality.

To formalize this point, consider an extension of the model in which each bank $b^j$ has an additional action at date 1, $A^j_1 = W(\tilde{z})$ for some $\tilde{z} \in [0,z]$. A bank that chooses $A^j_1 = W(\tilde{z})$ withdraws $\tilde{z}$ dollars of its debt claims on its forward neighbor bank at date 1, and rolls over the remaining $z - \tilde{z}$ dollars of its debt claims to date 2.

In this setting, consider a distressed bank with a positive liquidity need at date 1 (e.g., the original distressed bank $b^{\alpha(i)}$). This bank could try to obtain the required liquidity either by withdrawing its debt claims at date 1 (i.e., by choosing $A^j_1 = W(\tilde{z})$ for some $\tilde{z} > 0$) and/or by taking a precautionary action at date 0 (i.e., by choosing $A^j_0 \in B$). Choosing $A^j_0 = B$ is strictly costly for the bank because it sacrifices equity value at date 2. However, withdrawing debt claims is not costly. In fact, either the forward neighbor bank is insolvent, in which case withdrawing is strictly better than rolling over (recall that each bank is small and takes the debt payment of the forward neighbor bank as given), or the forward bank is solvent in which case withdrawing and rolling over generate the same amount of equity value. Hence, the bank always prefers ex-post withdrawal to the ex-ante precautionary actions. In other words, the liquidity pecking order is such that a bank that will need liquidity at date 1 first chooses $A^j_1 = W(\tilde{z})$, and then (if there is need) resorts to ex-ante precautionary measures.

Next consider the original distressed bank, $b^{\sigma(i)}$, that will need at least $\theta$ dollars of liquidity. This bank withdraws a positive amount of its debt claims from its forward neighbor, i.e., $A^{\sigma(i)}_1 = W(\tilde{z})$ for some $\tilde{z} > 0$. This puts bank $b^{\sigma(i+1)}$ also in need of $\tilde{z}$ dollars of liquidity, which also withdraws $\tilde{z}$ units of its debt claims on the forward neighbor. As in Allen and Gale (2000), this triggers further withdrawals until, in equilibrium, $A^j_1 = W(\tilde{z})$ for all $j$. Hence, the original distressed bank tries, but cannot obtain, any net liquidity
through cross debt withdrawals. In particular, this bank still needs at least $\theta$ dollars of
liquidity after cross debt withdrawals. This further implies that, in equilibrium, the bank
withdraws all of its debt claims, i.e., $\tilde{z} = z$. Thus, no bank rolls over its debt and all
debt claims are settled at date 1. It follows that the equilibria analyzed in the main text
continue to be the equilibria in this setting with a more general action space at date 1.

This analysis also illustrates the network-liquidity externality. A distressed bank can
obtain liquidity through two distinct sources: it can either withdraw its debt claims on
the forward neighbor bank, or it can hoard its liquid reserves and sell legacy loans. In
view of the banks’ liquidity constraints, a bank that chooses the former option puts its
forward neighbor bank also in distress, imposing a network-liquidity externality on it. In
particular, if the bank decides to withdraw its debt claims, the forward neighbor bank
scrambles for liquidity and faces insolvency if it is unable to meet this liquidity demand.

As the above analysis shows, a distressed bank in our setup always prefers to withdraw
the debt claims.\textsuperscript{12} In Appendix A.2 we study the polar opposite case, enforced by the
government, in which a bank that needs liquidity first hoards its own liquid reserves, and
thus avoids inflicting a network-liquidity externality whenever it can. Our analysis shows
that internalizing network-liquidity externalities in this fashion leads to shorter cascades
in aggregate (see Proposition 3 in the appendix).

Intuitively, the scramble for liquidity is like a hot potato which the banks can either
pass straight to their neighbors, or which they can cool down a bit using their resources
before passing it on. When all banks pass it without cooling it, the hot potato eventually
reaches a vulnerable bank, i.e., a bank which is sufficiently close to the original distressed
bank. This bank cannot pass the potato to its neighbor, which is already bankrupt.
Moreover, the resources of this bank alone are not sufficient to cool down the potato
hence the bank burns (i.e., it cannot meet the liquidity demand and becomes insolvent),
which lengthens the cascade. In contrast, when each bank cools down the potato before
passing it on, then the potato is cold before it reaches the vulnerable bank, leading to a
much shorter cascade.

\section{Conclusion}

In this paper we provide a model that illustrates how fire sales can arise even when financial
markets are deep and the shock is small relative to the wealth in the financial network.

\textsuperscript{12}The bank’s preference for liquidity withdrawal is strict if the forward neighbor pays $q^j_2 < R$. In
the more general model analyzed in Caballero and Simsek (2009), the bank always strictly prefers to
withdraw deposits and thus always inflicts a liquidity externality.
The key ingredient for this outcome is the complexity of the financial network and the uncertainty this features generates once banks are unable to figure out their exposure to an indirect hit.

We also show that there is a powerful feedback between fire sales and perceived complexity. More severe fire sales lengthen the potential cascades, and raise the complexity of the environment. This triggers confusion among potential asset buyers, which pull back and exacerbate the fire sale. In extreme scenarios these potential buyers can turn into sellers, leading to a complete collapse in secondary markets.

We did not explore policy questions, but it is apparent that our environment creates many policy opportunities during crises. For example, the complexity externality supports government actions that shorten the cascade (e.g., bailing out distressed banks, supporting loan prices, providing additional liquidity) or that reduce the network uncertainty (e.g., stress testing and widespread guarantees to banking liabilities or assets). More conventionally, the fire-sale externality supports policies that relax the liquidity constraints (e.g., providing additional liquidity, supporting loan prices), and the network-liquidity externality supports actions that reduce banks’ local interactions (e.g., moving OTC transactions to exchanges).

A question that emerges in our environment is whether banks can aggregate their (local) information about the financial network. In our model, banks cannot credibly share their information if we assume that distressed banks suffer losses from revealing that they are distressed (which is likely to be the case in reality). This is because banks that are close to the original distressed bank have an incentive to misreport their distance, which prevents the aggregation of information. More broadly, one could imagine many other reasons why information production and sharing during a crisis is inefficient, which emphasizes the importance of policies that provide information (e.g., stress testing, collecting data on OTC transactions).

As a parting thought we note that the particular insolvency motive we consider raises the question of what would happen if the distressed institutions chose to gamble for resurrection by not selling their assets, which would improve their outcome in good states at the cost of a greater bankruptcy risk. Our model suggests that gambling for resurrection may be a mixed blessing for the aggregate. Gambling by potential buyers, that is, institutions that are far from the cascade but that do not know this, would limit the fire sales and the downward spiral of prices. On the other hand, gambling by institutions near the cascade would increase the cascade size and trigger the complexity mechanism. This issue also points to important policy trade-offs for the decision on which institutions to guarantee during a systemic event.
A Appendix

A.1 Proofs Omitted in the Main Text

Proof of Lemma 2

Case (i): $K(p) \leq 1$. To prove that the conjectured actions and payments constitute an equilibrium, first note that the original distressed bank optimally chooses $A_0^{(i)} = S$ and pays out the same level $Q_1[0]$ that it would pay in the no-uncertainty economy (since it receives the full amount $z$ from its forward neighbor, $b^{(i+1)}$, which is solvent in the conjectured equilibrium). Next consider the bank with distance $k = 1$. Under the conjectured equilibrium, this bank knows that it will receive $x = Q_1[0]$ from its forward neighbor, which is equal to what it would receive in the no-uncertainty economy. Hence, it optimally chooses the same action it would choose when information is free.

Consider next a bank with distance $k \geq 2$. This bank is uncertain about its distance, thus it chooses its date 0 action as if it will receive $x = Q_1[1]$ from its forward neighbor. Under the conjectured equilibrium, the cascade size is $K(p) \leq 1$, thus we have $Q_1[1] = z$. Hence, the bank’s liquidity need, (6), is zero (even in the worst case scenario of $\tilde{k} = 2$). Thus, it optimally chooses $A_0^i = B$, verifying the optimality of the conjectured action.

Since the banks’ actions are the same as the no-uncertainty economy, their payments are also identical to that case, which verifies (by Lemma 1) that the equilibrium is distance based and monotonic.

Case (ii): $K(p) \geq 2$. Similar to the previous case, the original distressed bank and the bank with distance $k = 1$ optimally choose the same action and make the same payments as in the no-uncertainty economy.

Consider next a bank with distance $k \geq 2$. This bank is uncertain about its distance, thus it chooses its date 0 action as if it will receive $x = Q_1[1]$ from its forward neighbor. Since $K(p) \geq 2$, under the conjectured equilibrium, we have $Q_1[1] < z$ (which is equal to its level in the no-uncertainty benchmark). Hence, the bank with distance $k \geq 2$ expects (in the worst case scenario) to have a positive liquidity need. Thus, it optimally chooses the precautionary action, $A_0^i = S$ (cf. Section 3).

Next consider the banks’ debt payments and equity values. The banks with distance $k \leq K(p) - 1$ are solvent and their debt payments and equity values are the same as in the no-uncertainty economy. The transition bank with distance $K(p)$ is solvent and its debt payment and equity value is also the same as in the no-uncertainty economy. The
banks with distance \( k \geq K(p) + 1 \) are also solvent and they pay \( Q_1[k] = z \) on their debt. However, the equity values of these banks are different than the no-uncertainty economy. In particular, the equity value of a bank with distance \( k \geq K(p) + 1 \) is given by

\[
Q_2[k] = y + (1 - y)p < R.
\]

This discussion also establishes that the equilibrium is distance based and monotonic, completing the proof.

### A.2 Equilibrium without Network-liquidity Externalities

In the main text, the bank always considers withdrawing its debt claims as the first source of liquidity (cf. Section 5.3), thus imposing a network-liquidity externality on its forward neighbor bank. To clarify the role of network-liquidity externalities, in this appendix we analyze the equilibrium under a government policy that enforces banks to roll over their debt claims unless they have used all of their liquid reserves.

To facilitate the analysis, it helps to consider a slightly greater action space for banks:

\[
(A^0_j, A^1_j) \in \{H(\tilde{y}), S, B\} \times \{W(\tilde{z})\},
\]

where the two date 0 actions, \( \{S, B\} \), are the same as in the main text and the date 1 actions \([W(\tilde{z})]_{\tilde{z} \in [0,1]}\) are the same as in Section 5.3. In addition, we allow banks to take the date 0 actions, \([H(\tilde{y})]_{\tilde{y} \in [0,y]}\), where \( A^0_j = H(\tilde{y}) \) denotes that the bank hoards \( \tilde{y} \in [0,y] \) units of its flexible reserves and does not sell any legacy loans. In other words, \([A^0_j = H(\tilde{y})]_{\tilde{y} \in [0,y]}\) correspond to a range of intermediately precautionary actions. In Caballero and Simsek (2009), we analyze the equilibrium with this more general action space and we show that the qualitative properties of the equilibrium are unchanged.

Next, we introduce the main assumption of this appendix: the government enforces a liquidity pecking order so that banks do not impose a network-liquidity externality on their forward neighbors, whenever they can avoid doing so.

**Assumption (LPO).** Consider a bank that needs liquidity at date 1 and whose forward neighbor bank is able to promise a payment of \( z \) dollars at date 2. The government imposed liquidity pecking order for this bank is such that the bank first considers hoarding its flexible reserves, i.e., it considers the action \( A^0_j = H(\tilde{y}) \). The bank withdraws some of its debt claims (chooses \( A^1_j = W(\tilde{z}) \)) only if \( A^0_j = H(y) \) is not sufficient to meet its liquidity demand.
Finally, to illustrate our point starkly, we make a parametric assumption

\[ z < (1 - y) R, \quad (18) \]

which ensures that the date 2 value of a bank’s own legacy loans are enough to pay all of its short term debt (if it is rolled over). Under these assumptions and when \( n \) is sufficiently large, we conjecture that there is an equilibrium in which all banks with distance \( k \geq 1 \) (i.e., all banks except potentially the original distressed bank) are solvent. In other words, the cascade size is at most 1, in contrast with the equilibria characterized in Propositions 1 and 2.

If \( \theta < y \), then the original distressed bank \( b_{\theta}^{(i)} \) is able to meet its liquidity demand by hoarding its flexible reserves, and the cascade size is 0. If instead \( \theta > y \), then bank \( b_{\theta}^{(i)} \) withdraws \( \bar{z} \equiv \min (\theta - y, z) \), i.e., it chooses \( A_{1}^{(i)} = W (\bar{z}) \), which puts bank \( b_{\theta}^{(i+1)} \) in need of \( \bar{z} \) dollars of liquidity. Under the assumption for the liquidity pecking order, bank \( b_{\theta}^{(i+1)} \) (with distance \( n - 1 \)) first resorts to hoarding its flexible reserves. If \( \bar{z} \leq y \), then this bank chooses \( \left( A_{0}^{(i+1)} = H (\bar{z}), A_{1}^{(i+1)} = W (0) \right) \), that is, the bank meets its liquidity payments purely by hoarding its flexible reserves, and it rolls over its short term debt claims. Otherwise \( \bar{z} > y \) and this bank chooses \( \left( A_{0}^{(i+1)} = H (y), A_{1}^{(i+1)} = W (\bar{z} - y) \right) \), i.e., it withdraws \( \bar{z} - y < z \) of its debt claims. In this case, consider bank \( b_{\theta}^{(i+2)} \) with distance \( n - 2 \), which needs \( \bar{z} - y \) dollars of liquidity. This bank’s response is similar to bank \( b_{\theta}^{(i)} \): if \( \bar{z} - y \leq y \), then the bank meets its liquidity payment purely by hoarding its flexible reserves, and otherwise it withdraws an even smaller amount from its forward neighbor.

It follows that a pattern emerges for the banks’ cross withdrawal decisions. In particular, let \( \bar{n} \geq 1 \) denote the unique integer such that

\[ y \bar{n} \geq \bar{z} = \min (\theta - y, z) > y (\bar{n} - 1) \]

and suppose \( n > \bar{n} \). Then, for each \( j \in \{1, \ldots, \bar{n} - 1\} \), the bank \( b_{\theta}^{(i+j)} \) with distance \( n - j \) chooses \( \left( A_{0}^{(i+j)} = H (y), A_{1}^{(i+j)} = W (\bar{z} - jy) \right) \), while the bank \( b_{\theta}^{(i+n)} \) with distance \( n - \bar{n} \) chooses \( \left( A_{0}^{(i+n)} = H (\bar{z} - (\bar{n} - 1) y), A_{1}^{(i+n)} = W (0) \right) \). Since the bank with distance \( n - \bar{n} \) keeps its debt claims, the remaining banks with distance \( k \in \{1, \ldots, n - \bar{n} - 1\} \) do not need any liquidity, and these banks roll over their short term debt claims if and only if their forward neighbors can promise at least \( z \) dollars at date 2.

Next consider the backward neighbor bank \( b_{\theta}^{(i-1)} \) of the original distressed bank. If the original distressed bank is insolvent (which is the case when \( \theta > l (p) \)), then bank
bank $b^{(i-1)}$ chooses $A_i^{(i-1)} = W(z)$ and receives a payment $q_i^{(i)} < z$. Despite incurring some losses, in view of condition (18), bank $b^{(i-1)}$ is able to promise its debt holders at least $z$ dollars at date 2. Since the backward neighbor bank $b^{(i-2)}$ does not need liquidity, it chooses to roll over its debt claims in bank $b^{(i-1)}$ in view of assumption (LPO). Repeating this reasoning, all banks with distances $k \in \{1, \ldots, n-\bar{n}-2\}$ are able to promise $z$ dollars at date 2, and their backward neighbor banks choose to roll over their debt claims in view of assumption (LPO).

Note also that there is one seller in the conjectured equilibrium (the original distressed bank $b^{(i)}$) while the banks with distance $k \in \{2, \ldots, n-\bar{n}-1\}$ are potential buyers of loans. Hence, under the deep secondary market assumption (i.e., the analogue of condition (13) for this setup),

$$(n-\bar{n}-2)y > 1-y,$$

the unique equilibrium price is given by $p = 1$. Note also that this analysis applies regardless of whether the banks know the financial network $b(\sigma)$ or whether they only have local knowledge (i.e., they know only their forward neighbor). We summarize this result in the following proposition.

**Proposition 3.** Suppose the banks’ action space is extended to (17), assumption (LPO) holds (which is imposed by the government), and condition (19) is satisfied. Then, regardless of whether the banks know the financial network $b(\sigma)$ or just their forward neighbor, there is an equilibrium in which loan prices are given by $p = 1$ and the cascade size is either 0 or 1. At date 1, the banks with distance $k \in \{1,0,n-1,\ldots,n-\bar{n}-1\}$ withdraw all or some of their debt claims, while the banks with distance $k \in \{2,3,\ldots,n-\bar{n}\}$ roll over their debt claims in the forward neighbor bank.

Proposition 3 establishes our main result in this appendix: If the banks avoid inflicting a network-liquidity externality, then the cascade size is much shorter relative to the cases analyzed in Propositions 1 and 2. To see the intuition, consider the equilibrium in Proposition 3 and consider what the banks would do if we removed the government imposed liquidity pecking order in assumption (LPO). Consider bank $b^{(i+\bar{n})}$, which meets its liquidity demand from its backward neighbor purely by hoarding its flexible reserves. For this bank, hoarding reserves delivers 1 dollars of liquidity at a cost of $R$ dollars (at date 2), while withdrawing debt claims would deliver 1 dollars of liquidity at a cost of 1 dollar at date 2. Hence, if not restricted by government policy, bank $b^{(i+\bar{n})}$ would strictly prefer to withdraw its debt claims to hoarding liquidity, which would put bank $b^{(i+\bar{n}+1)}$ in distress. Similarly, absent government policy, bank $b^{(i+\bar{n}+1)}$ would prefer to withdraw its debt claims and the scramble for liquidity would continue to cascade in similar fashion.
Eventually, a *vulnerable* bank, $b^{(i-1)}$, which is sufficiently close to the original distressed bank (and thus has incurred some losses) would become distressed. This bank might be unable to find the required liquidity and might become insolvent. Hence, network-liquidity externalities have the potential to make vulnerable banks go insolvent. The government imposed liquidity order in assumption (LPO) internalizes these externalities, which in turn ensures that the cascade size is shorter.
References


