A Financial Accelerator through Coordination Failure

Short title: Financial Accelerator Coordination Failure

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Abstract

This paper studies the effect of liquidity crises in short-term debt markets in a dynamic general equilibrium framework. Creditors (retail banks) receive imperfect signals regarding the profitability of borrowers (wholesale banks) and, based on these signals and their beliefs about other creditors' actions, choose whether to rollover funding, or not. The uncoordinated actions of creditors cause a suboptimal incidence of rollover, generating an illiquidity premium. Leverage magnifies this coordination inefficiency. Illiquidity shocks in credit markets result in sharp contractions in output. Policy responses are analyzed.

Keywords: Financial frictions, DSGE models, Global games, Bank runs, Unconventional monetary policy, Financial crises.

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1 Introduction

Creditors financing a project face a coordination problem. Fear of other creditors not rolling over funding may lead to preemptive action, undermining the project, and the chance of repayment to those creditors as well. Coordination problems impact the functioning of many types of the credit market but often the most visible manifestation of coordination failure is a bank run.[1] At least since Bagehot (1873)'s description of the 1866 financial panic, economists have acknowledged the inherent fragility of financial intermediaries. Table 1 lists notable bank runs during the 2007-08 financial crisis. The demise of Northern Rock (UK) and Lehman Brothers (US), for example, have been interpreted (see Brunnermeier (2009) and Shin (2009)) as events in which short-term interbank market creditors were unwilling to continue lending to these institutions, for fear that other creditors were doing likewise.[2]

This paper makes three contributions. First, it builds a rigorously microfounded coordination problem in credit markets in a dynamic general equilibrium model. Second, the model highlights the role that maturity- and liquidity-mismatch play in the propagation of shocks through the economy. Third, it provides a laboratory to study the effect of unconventional policy responses to a large-scale liquidity dry up, as in the 2007-08 financial crisis.

To the best of my knowledge, this paper was the first to model liquidity and bank runs within a dynamic general equilibrium framework.[3] Recently, Gertler and Kiyotaki (2015) and Gertler et al. (2016) also studied the macroeconomic implications of bank runs. My contribution distinguishes itself from these in two important respects. First, in the aforementioned papers bank runs are themselves aggregate shocks to the economy in which the entire financial sector experiences a run. In reality, as Table 1 suggests, even during a major financial crisis, only a subset of all financial institutions experience a run. My model captures this feature. In particular, in any given period the proportion of borrowers in danger of experiencing a run is determined by the aggregate state, with the proportion of borrowers experiencing a run being endogenously countercyclical. Second, runs in the model are determined by a rigor-

[1] Coordination problems also impact the market for bank loans, commercial paper, and corporate bonds. For example, Hertzberg et al. (2011) exploit a natural experiment, which compelled banks to make public negative private assessments about their borrowers, to quantify the effect of coordination problems. Even the commercial paper market, primarily for low-default-risk firms, experienced liquidity dry ups, following the Penn Central bankruptcy (1970), Russia/LTCM crisis (1998), and Enron/WorldCom episode (2002). In 2008, the Fed introduced the Commercial Paper Funding Facility (CPFF) to prevent a market freeze. No issuers who used the CPFF defaulted on their debt obligations, suggesting the liquidity dry up was driven by coordination problems rather than increased insolvency risk. Disorderly liquidation of assets is economically inefficient. In the US, chapter 11 bankruptcy provision is designed to address the coordination problem among creditors (Jackson, 1986), giving legal protection to a firm to remain in business while being restructured.

[2] In practice, it is difficult to disentangle whether the unwillingness of creditors to continue lending hastened the bankruptcy of an insolvent bank or whether the run scuppered a sound institution. Morris and Shin (2016) disentangle the two in theory.

[3] The first version of this paper was circulated in 2010.

ously microfounded global game. In contrast, Gertler and Kiyotaki (2015) and Gertler et al. (2016) use an ad hoc threshold rule (based on the insights from the global games literature).

Table 1: Notable runs during the 2007-08 financial crisis

2007 Aug	Countrywide Financial	US	Wholesale funding run followed by a retail-deposit run.
2007 Sep	Northern Rock	UK	Wholesale funding run followed by a retail-deposit run.
2008 Mar	Bear Stearns	US	Wholesale funding run.
2008 Jul	IndyMac	US	Retail-deposit run.
2008 Sep	Lehman Brothers	US	Wholesale funding run.
2008 Sep	Washington Mutual	US	Retail deposit run.

Source: Online Appendix C.1.

In my model, wholesale banks (*the borrowers*) finance themselves with short-term debt from a multitude of retail banks (*the creditors*). I show that coordination problems among creditors results in a suboptimal incidence of debt rollover and generates an equilibrium trade off between borrower leverage and the illiquidity premium paid on external finance. In aggregate, the coordination problem amplifies business cycle dynamics and shocks to credit market liquidity generate a novel channel of additional volatility in economic activity. I study two potential policy instruments to dampen the effect of an illiquidity crisis: *direct lending* to and *equity injections* into wholesale banks. I show, for a given dollar amount committed, that equity injections dampen the contemporaneous effect on economic activity more than direct lending, but causes output to remain subdued for longer. This is because a dollar of debt intermediated by the policymaker improves the solvency of a wholesale bank (which largely determines the extent of the coordination problem) by less than a dollar of additional equity. However, equity injections disincentivize balance sheet adjustment, slowing the output recovery following the shock.

Coordination failure arises from two assumptions. One, borrowers have a balance sheet maturity mismatch with longer maturity (more illiquid) assets and shorter maturity (more liquid) liabilities. Two, each borrower has multiple creditors that cannot coordinate their actions. When a borrower's debt matures, each creditor must decide whether to rollover, taking account of fundamentals and the actions of other creditors. Diamond and Dybvig (1983) study this coordination problem with depositors as the creditors and find the existence of multiple equilibria, one of which is a bank run.[4] Such multiple equilibria, however, are problematic for a general equilibrium framework where the endogenous pricing of debt requires ex

[4]See Gorton and Winton (2003) for a review of the literature Diamond and Dybvig (1983) spawned.

ante knowledge about the probability distribution of ex post outcomes. In this instance global games offer a solution.[5] Multiple equilibria in Diamond and Dybvig (1983) are a consequence of the assumption that creditors' information sets are perfectly symmetric. By introducing idiosyncratic noise into creditors' signal of a borrower's solvency, the global games literature shows that a unique set of self-fulfilling beliefs prevail in equilibrium. I thus model the coordination problem in credit markets as a sequence of micro-founded static global games, building on Morris and Shin (2004), Rochet and Vives (2004), and Goldstein and Pauzner (2005). The resulting dynamic general equilibrium model allows the study of the macroeconomic effects of illiquidity shocks and the efficacy of alternative policy interventions.[6]

Heider et al. (2015) study liquidity hoarding and interbank lending during the crisis in a 3-period partial equilibrium model. However, theories of coordination problems in credit markets have received relatively little attention in the macroeconomics literature. The majority of the financial friction literature has broadly followed two paths which find their roots in the work of Bernanke and Gertler (1989) (building on the costly state verification (CSV) assumption from Townsend (1979), in which there is an informational asymmetry in a single borrower-creditor relationship) and Kiyotaki and Moore (1997) (building on the hold-up assumption of Hart and Moore (1994), introducing a binding collateral constraint on lending).[7] The distortion created by coordination problems among creditors is a distinct and salient feature of credit markets, especially during the 2007-08 financial crisis. This paper, therefore, is an important complementary framework to analyze credit market interventions. Related papers modeling the policy response of the Fed, Treasury, and other central banks and governments to the financial crisis in the context of alternative financial frictions include Gertler and Kiyotaki (2010) and Gertler and Karadi (2011).[8]

The rest of the paper is structured as follows: Section 2 presents the model; Section 3 analyzes comparative statics of the global game and the dynamic response of the model to illiquidity shocks; Section 4 analyzes direct lending and equity injections; and Section 5 concludes.

[5] The seminal contribution is Carlsson and van Damme (1993). For an overview, see Morris and Shin (2003). Corsetti et al. (2004) apply global games to currency crises. Global games is one among several possible equilibrium selection devices. Adopting the global games approach is appealing for several reasons: It relaxes the assumption of common knowledge and payoffs in an intuitive and small way and accounts for the correlation of runs and bad fundamentals.

[6] Kurlat (2013) and Dang et al. (2012) explain why the market for some assets freeze during crises.

[7] Seminal contributions include Carlstrom and Fuerst (1997) and Bernanke et al. (1999); Iacoviello (2005) applies financial frictions to the housing market; Christiano et al. (2014) estimates the importance of financial risk shocks; Carlstrom et al. (2010), Fiore and Tristani (2013), and Cúrdia and Woodford (2016) analyze optimal monetary policy with financial frictions; Angeloni and Faia (2013) model macroprudential policy. de Groot (2016) reviews the financial accelerator literature.

[8] See also Sargent and Wallace (1982), Reis (2009b), and Cúrdia and Woodford (2010).

2 The model

The model is a canonical real business cycle model in which I embed a coordination problem facing retail banks in financing wholesale banks.

2.1 Households

A representative household consumes, C_t, supplies labor, L_t, and has preferences given by

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\sigma_C}}{1-\sigma_C} - \chi \frac{L_t^{1+\rho}}{1+\rho} \right). \tag{1}$$

The household maximizes (1) subject to its budget constraint given by

$$C_t \leq W_t L_t + R_{t-1} D_{t-1} - D_t + \Pi_t, \tag{2}$$

where W_t is the real wage; R_t is a predetermined risk-free rate on deposits, D_t, held with retail banks; and Π_t are profits (from owning goods producing firms and capital producers). The household's first-order conditions are given by

$$W_t = \chi L_t^{\rho} C_t^{\sigma_C}, \tag{3}$$

$$1 = \beta \mathbb{E}_t \left(C_{t+1}/C_t \right)^{-\sigma_C} R_t. \tag{4}$$

2.2 Capital producers

The production of new capital is subject to adjustment costs. A representative capital producer takes I_t consumption goods and transforms them into $\Psi\left(I_t/I\right) I$ units of capital that it sells at price Q_t (where I is the steady state level of investment). I assume the function Ψ is concave, $\Psi(1) = \Psi'(1) = 1$, and $\Psi''(1) = -\psi$. Profits are given by $Q_t \Psi\left(I_t/I\right) I - I_t$. The producer's first-order condition is given by

$$Q_t = \left(\Psi' \left(I_t/I \right) \right)^{-1}. \tag{5}$$

The aggregate capital stock at the end of period t is given by

$$K_t = (1-\delta) K_t^* + \Psi\left(I_t/I\right) I, \tag{6}$$

where K_t^* is capital available for time t production. This is different from the capital stock at the end of $t-1$ as some is lost due to the costly uncoordinated liquidation of failing banks.

2.3 Goods producers

Goods producing firms hire labor and rent capital as inputs to a constant returns to scale technology to produce output, Y_t, given by

$$Y_t = A_t \left(K_t^*\right)^{\alpha} L_t^{1-\alpha}, \tag{7}$$

where A_t is the stochastic level of technology. Output is sold in a perfectly competitive market at a unit price. The firm's first-order conditions are given by

$$MPK_t = \alpha Y_t / K_t^*, \tag{8}$$

$$W_t = (1-\alpha) Y_t / L_t, \tag{9}$$

where MPK_t is the marginal product of capital. In the absence of coordination failure, arbitrage ensures that the risk-adjusted return on capital equals the risk-free rate

$$\mathbb{E}_t \left(\left(C_{t+1}/C_t\right)^{-\sigma_C} R_{K,t+1} \right) = \mathbb{E}_t \left(\left(C_{t+1}/C_t\right)^{-\sigma_C} \right) R_t, \tag{10}$$

where $R_{K,t} \equiv \left(MPK_t + (1-\delta) Q_t\right) / Q_{t-1}$.

2.4 Retail and wholesale banks

The financial sector is made up of retail and wholesale banks. Retail banks accept household savings and lend to wholesale banks who finance firms to rent capital. By assumption, wholesale banks rely on short-term debt funding from a large number of retail banks. As a result, retail banks face a coordination problem in deciding whether to rollover maturing debt.[9]

Wholesale banks Wholesale banks act as *capital managers*. They invest in firms' capital with the intention of augmenting the capital with their idiosyncratic productivity and earning a return from the augmented capital. Formally, there is a continuum of wholesale banks indexed by w with preferences linear in consumption. At the end of $t-1$, a wholesale bank purchases capital, K_{wt-1}, at price Q_{t-1} financed with net worth, N_{wt-1}, and external financing from the full continuum of retail banks. This external finance takes the form of short-term debt: 1) At an intra-period stage of time t retail banks decide whether to rollover the debt. 2) Rolled over debt is scheduled for repayment at the end of t. Thus, a wholesale bank's balance sheet has a maturity mismatch; its assets (capital) earn a return at the end of t but its liabilities (the debt) must be rolled over intra-period.[10]

[9] Table 2 summarizes the timing of events in a given period.

[10] The maturity mismatch is not beneficial per se, as in, Diamond and Dybvig (1983) where some depositors

At the end of $t-1$ wholesale banks are homogeneous in all respects except net worth. Thus, leverage, $\ell_t = Q_t K_{wt}/N_{wt}$, and the interest rate on debt will be common across banks. At the beginning of t, wholesale bank w observes its idiosyncratic productivity that will transform its capital to $\omega_{wt} K_{wt-1}$, where ω_{wt} is iid across time and space, $\mathbb{E}(\omega_{wt}) = 1$, with cdf F, pdf f, and support on $[0, \infty)$. The distribution is common knowledge and assumed to be log-normal. The aggregate return per unit of productive capital, $\omega_{wt} K_{wt-1}$, is given by $R_{K,t}$. The contract specifies a non-default interest rate, $R_{L,t}$.[11] If a retail bank does not rollover at the intra-period stage, the debt must be repaid immediately with interest rate $\tilde{R}_{L,t} = R_{L,t}/R_{K,t}$.[12]

Table 2: Timing in a given period

1.	The aggregate state, $\{A_t, \lambda_t\}$, is realized and $\bar{\omega}_t$ is determined from a state-contingent menu.
2.	The idiosyncratic productivity, ω_{wt}, of each wholesale bank is realized.
3.	Retail banks receive signals ω_{rwt} and decide whether to rollover funding.
4.	Banks with capital use their idiosyncratic productivity, ω_{wt} or γ, to augment their capital.
5.	The augmented capital is rented to goods producers at rental rate MPK_t.
6.	After production, capital is sold to the capital producers at price Q_t.
7.	Wholesale banks repay retail banks and retail banks repay households.
8.	A measure, $1-\upsilon$, of wholesale banks exit and a new measure, $1-\upsilon$, enter.
9.	Wholesale banks buy capital, K_{wt}, at price Q_t using net worth, N_{wt}, and new external financing.

Suppose all retail banks rollover. It is then possible to define a wholesale bank's solvency condition in terms of a cutoff value of idiosyncratic productivity, denoted by $\bar{\omega}_t$, such that the wholesale bank has just enough resources to repay the debt, given by

$$\bar{\omega}_t R_{K,t} \ell_{t-1} = R_{L,t} \left(\ell_{t-1} - 1\right). \tag{11}$$

However, retail banks need not rollover. If a retail bank does not rollover, the wholesale bank pays $\tilde{R}_{L,t} \left(Q_{t-1} K_{wt-1} - N_{wt-1}\right)$ in units of capital (since the wholesale bank has no other assets at the intra-period stage). Using (11), this is equivalent to $\bar{\omega}_t Q_{t-1} K_{wt-1}$. Transferring

have liquidity needs at the intra-period stage. Instead, the market structure is motivated by Brunnermeier and Oehmke (2013)'s *maturity rat race* in which a negative externality arises because short maturity claims dilute the value of long maturity claims, causing a borrower to successively move towards short-term financing, with complete short-term financing the only stable equilibrium.

[11] Following Bernanke et al. (1999), the debt contract has wholesale banks absorb the aggregate risk. Retail banks hold a portfolio of wholesale bank debt that perfectly diversifies idiosyncratic risk. Thus, retail banks hold safe portfolios with a predetermined return that can be passed on to depositors. Carlstrom et al. (2016) and Dmitriev and Hoddenbagh (2017) study the consequences of (optimal) state-contingent deposit contracts.

[12] This assumption reduces the complexity of the debt contract and since $R_{L,t} > \tilde{R}_{L,t}$ does not materially change the behaviour of the model.

capital, however, incurs a cost: For every unit of capital transferred at the intra-period stage, the wholesale bank loses $1 - \lambda_t$ units of capital, where $\lambda_t \in (0, 1)$ is an exogenous stochastic measure of the liquidity of wholesale banks' assets.

When one is forced to sell an asset quickly in an illiquid market, one must content oneself with a price for the asset below its fundamental value. This "fire sale" feature of credit markets is captured by λ_t.[13] Thus, wholesale banks' balance sheets not only exhibit a maturity mismatch, but also a liquidity mismatch. The intra-period value of a wholesale bank's capital is $\lambda_t K_{wt-1}$ while the claims on the wholesale bank, if no retail banks rollover, is $\bar{\omega}_t K_{wt-1}$. When the interest rate is such that $\bar{\omega}_t > \lambda_t$, the wholesale bank is illiquid and vulnerable to a credit run. Online Appendix A.1 provides conditions under which $\bar{\omega}_t$ (which is endogenous) is greater than λ_t in equilibrium. Thus, the coordination problem is an endogenous phenomenon.

Retail banks and the rollover decision Retail banks are perfectly competitive, pay a risk-free return for deposits from households and hold a fully diversified portfolio of wholesale banks' short-term debt. Retail banks choose whether to rollover the debt at an intra-period stage. By not rolling over, a retail bank receives a fraction of the wholesale bank's capital and earns a return by taking over the capital management process (i.e. augmenting the capital itself and renting the augmented capital to firms).

This section solves the retail banks' rollover decision rule, conditional on a given debt contract specified by $\{\ell_{t-1}, \bar{\omega}_t\}$. At the beginning of t, each retail bank, indexed by r, observes a noisy signal of each wholesale bank's idiosyncratic productivity, $\omega_{rwt} = \omega_{wt} + \varepsilon_{rwt}$. The noise term, $\varepsilon_{rwt} \sim U(-\bar{\varepsilon}, \bar{\varepsilon})$, is iid across time and space. Given the signals, retail banks decide individually, for each wholesale bank, whether to rollover funding.

A retail bank's payoff (to rolling over or not) depends on a wholesale bank's realized idiosyncratic productivity and on the actions of other retail banks. Depending on the value of λ, there are four scenarios. "Scenario 1: No fragility" occurs when λ is close to 1. In this scenario the wholesale bank is never illiquid. In "Scenario 2: Mild fragility" wholesale banks that experience a run are technically already insolvent. In "Scenario 3: Acute fragility", even solvent wholesale banks face illiquidity and the risk of a run. Finally, "Scenario 4: No rollover" occurs when λ is extremely low and retail banks never rollover. The rest of this section focuses on solving the "Scenario 2: Mild fragility" equilibrium since this scenario corresponds to the estimated parameterization of the model in Section 3.2. The derivation of the other scenarios are in Online Appendix A.1. I provide illustrative comparative statics across all four scenarios and the full parameter space in Section 3.1.

[13] See Shleifer and Vishny (2011) for a review of the research on fire sales.

Table 3 presents a retail bank's payoff matrix (conditional on the Mild fragility scenario), where p_t is the proportion of retail banks that do not rollover and γ is the productivity of the retail bank (i.e. retail banks' equivalent of ω_{wt}). It measures retail banks' ability to do a wholesale bank's job: When $\gamma = 0$, retail and wholesale banks are complements in the financial sector—neither can do the others' job. When $\gamma \in (0, 1)$, there is some substitutability with retail banks able to earn a positive return from capital management.[14]

Table 3: Payoffs to retail banks

Rollover	Not rollover	
$\bar{\omega}$	$\gamma\bar{\omega}$	if $0 \leq p \leq \frac{\lambda}{\bar{\omega}}$ and $\omega \geq \frac{\bar{\omega}(1-p)\lambda}{\lambda - p\bar{\omega}}$
$\frac{\omega}{1-p}\left(1 - \frac{p\bar{\omega}}{\lambda}\right)$	$\gamma\bar{\omega}$	if $0 \leq p \leq \frac{\lambda}{\bar{\omega}}$ and $\omega < \frac{\bar{\omega}(1-p)\lambda}{\lambda - p\bar{\omega}}$
0	$\frac{\gamma\lambda}{p}$	if $\frac{\lambda}{\bar{\omega}} < p \leq 1$

Note: Payoffs are normalized by $R_{K,t}Q_{t-1}K_{wt-1}$, and are for a given retail bank's action regarding a given wholesale bank. Since the problem is a static, symmetric game, all time and bank indexes have been dropped.

Table 3 reads as follows. Top-left: A retail bank that rolls over earns the non-default return, $\bar{\omega}_t$, if and only if the fraction of retail banks that do not rolling over, p_t, is low and the wholesale bank's productivity, ω_{wt}, is high. Bottom-left: However, a retail bank that rolls over receives zero if the fraction of retail banks that do not rollover is so high ($p_t > \lambda_t/\omega_t$) that the wholesale bank runs out of capital. The Middle row is the intermediate outcome in which the wholesale bank survives the intra-period stage but cannot fully repay its debt at the end of t. Top-right: A retail bank that does not rollover receives $\bar{\omega}_t$, applies its own productivity, γ, and earns $\gamma\bar{\omega}_t$, if the fraction of retail banks that do likewise is low. Bottom-right: However, if the fraction of retail banks that do not rollover is high, the wholesale bank has insufficient liquid capital to survive and the liquid capital, λ_t, is divided equally among the retail banks that do not roll over, earning them $\gamma\lambda_t/p_t$.

The payoff structure exhibits *strategic complementarities*. Up to a critical p_t at which the wholesale bank fails (i.e. runs out of capital), the *net* payoff from rolling over (i.e. rollover minus not rolling over) decreases as p_t rises. Thus, retail banks face a strategic environment in which higher-order beliefs regarding the actions of other retail banks are important. Proposition 1 below states that a retail bank's action is uniquely determined by its signal: It only rolls over if its signal, ω_{rwt}, is above a threshold, denoted ω_t^*.

[14]The payoffs are derived in Online Appendix A.1. When γ is sufficiently high, retail banks have no incentive to lend to wholesale banks since they can earn a higher return by directly buying and managing capital.

Proposition 1 *There is a unique (symmetric) equilibrium in which a retail bank does not rollover if it observes a signal ω_{rwt} below threshold ω_t^*, and rolls over otherwise.*

Proof: See Online Appendix A.1.[15] In computing the threshold, ω_t^*, observe that a retail bank with signal $\omega_{rwt} = \omega_t^*$, must be indifferent between rolling over and not. The retail bank's posterior distribution of ω_{wt} is uniform over the interval $[\omega_t^* - \varepsilon, \omega_t^* + \varepsilon]$. Moreover, the retail bank believes that the fraction of retail banks not rolling over, p_t, is given by

$$p(\omega_w, \omega^*) = \begin{cases} 1 & \omega^* - \varepsilon_{rw} > \omega_w \\ \frac{1}{2} + \frac{\omega^* - \omega_w}{2\varepsilon_{rw}} \text{ if } & \omega^* - \varepsilon_{rw} \le \omega_w \le \omega^* + \varepsilon_{rw} \\ 0 & \omega_w < \omega^* + \varepsilon_{rw} \end{cases} .$$

Thus, the posterior distribution of p_t is uniform over $[0, 1]$. In the limit when $\bar{\varepsilon} \to 0$ the resulting indifference condition is given by

$$\int_{p=\frac{\lambda}{\bar{\omega}}}^{1} -\frac{\gamma\lambda}{p} dp + \int_{p=0}^{\frac{\lambda}{\bar{\omega}}} \left(\frac{\omega^*}{1-p} \left(1 - \frac{p\bar{\omega}}{\lambda}\right) - \gamma\bar{\omega} \right) dp = 0, \tag{12}$$

where solving for ω_t^* leads to Proposition 2.[16]

Proposition 2 *If the noise component of retail banks' signals is arbitrarily close to zero, the equilibrium rollover threshold, ω_t^*, is given by*

$$\omega_t^* = \gamma\lambda_t x_t (1 - \ln(x_t)) (x_t + (1 - x_t) \ln(1 - x_t))^{-1}, \tag{13}$$

where $x_t \equiv \lambda_t / \bar{\omega}_t$. It is a striking result of Proposition 1 that there exists a unique switching equilibrium, even when the noise term in retail banks' signals is arbitrarily close to zero. Thus, in equilibrium, wholesale banks never experience a partial run but experience a complete run or full rollover with probability $F(\omega_t^*)$ and $1 - F(\omega_t^*)$, respectively.

To see the inefficiency created by the coordination problem, consider the decision of a retail bank when it is the sole holder of a wholesale bank's debt (or, equivalently, a scenario in which retail banks can costlessly and credibly coordinate their actions).[17] If it does not

[15] The proof requires there exist lower and upper dominance regions, $[0, \omega^L)$ and (ω^H, ∞), in which a retail bank would not rollover and rollover, respectively, regardless the actions of other retail banks. This requirement is discussed in Online Appendix A.1. When retail banks receive a noiseless signal on the interval $[\omega^L, \omega^H]$, there are multiple equilibria. But, a grain of doubt for retail banks (i.e. $\bar{\varepsilon} > 0$ arbitrarily close to zero) leads to the starkly different (and very useful) result given in Proposition 1.

[16] This condition specifies ω^* for $\omega^* < \bar{\omega}$. The complete indifference condition is given in Online Appendix A.1.

[17] There are two benchmarks against which to gauge the inefficiency: 1) assume creditors can perfectly coordinate actions (as in the text); 2) assume long-term debt, eliminating the rollover decision and the

rollover it gets $\gamma\lambda_t$ and if it does it gets the lesser of $\bar{\omega}_t$ and ω_{wt}. The optimal action is to rollover when $\omega_{wt} > \gamma\lambda_t$. Thus, the efficient (coordinated) threshold, $\omega^*_{\text{eff}} = \gamma\lambda_t$, is lower than ω^*_t. Coordination problems create a wedge between the equilibrium and efficient rollover thresholds and as a result the probability and incidence of runs is suboptimally high. This leads to Proposition 3.

Proposition 3 *i) The inefficiency wedge, $\omega^*/\omega^*_{\text{eff}}$, is increasing with the illiquidity, $x = \lambda/\bar{\omega}$, of the wholesale bank: $\partial\left(\omega^*/\omega^*_{\text{eff}}\right)/\partial x < 0$. ii) In the limit, when the wholesale bank is not illiquid, there is no inefficiency:* $\lim_{x\to 1}\left(\omega^*/\omega^*_{\text{eff}}\right) = 1$.

To get a sense of the dynamic implications, suppose the interest rate (and thus $\bar{\omega}_t$) moves countercyclically. This implies that in a recession, for a given λ_t, the distortionary effects of coordination problems in the credit market are magnified, generating a financial accelerator.

The debt contract A wholesale bank debt contract can be characterized by the pair $\{\ell_t, \bar{\omega}_{t+1}\}$. Since retail banks are perfectly competitive and pay a predetermined return to depositors, R_t, the debt contract must satisfy a zero profit break-even condition for retail banks. And since retail banks hold fully diversified debt portfolios, a retail bank's expected (normalized) payoff is given by

$$\underbrace{\bar{\omega}\int_{\bar{\omega}}^{\infty} f(\omega)\, d\omega}_{\substack{\text{i. Rolled over}\\ \text{and paid in full}}} + \underbrace{\int_{\omega^*}^{\bar{\omega}} \omega f(\omega)\, d\omega}_{\substack{\text{ii. Rolled over}\\ \text{and default}}} + \underbrace{\gamma\lambda_t \int_0^{\omega^*} f(\omega)\, d\omega}_{\substack{\text{iii. Not rolled}\\ \text{over}}}, \tag{14}$$

an integral over three possible outcomes:[18] The wholesale bank i) survives the intra-period stage and repays its debt in full; ii) survives the intra-period stage but is insolvent resulting in partial payment; or iii) does not survive and retail banks earn a return managing the capital themselves. We can rewrite (14) as $\Gamma_t - G_t$ where

$$\Gamma \equiv \bar{\omega}\int_{\bar{\omega}}^{\infty} f(\omega)\, d\omega + \int_0^{\bar{\omega}} \omega f(\omega)\, d\omega \quad \text{and} \quad G \equiv \int_0^{\omega^*} (\omega - \gamma\lambda_t) f(\omega)\, d\omega. \tag{15}$$

Thus, $1 - \Gamma_t$ and $\Gamma_t - G_t$ are the fraction of gross returns accruing to wholesale and retail banks, respectively, where G_t captures the deadweight loss resulting from coordination failure.

coordination problem. Under 1), it is efficient to coordinate and not rollover for wholesale banks with extremely low ω_{wt} values (i.e. $\omega^*_{\text{eff}} > 0$)—even after accounting for the liquidation cost, retail banks' ability to manage capital means they are able to generate a higher return. It is therefore possible to form a ranking: Short-term contracts with perfect coordination are preferred to long-term contracts, but long-term contracts are preferred to short-term contracts without coordination.

[18] This assumes $\omega^*_t < \bar{\omega}_t$. See Online Appendix A.1 for when this does not hold.

The contracting problem maximizes the wholesale banks' return subject to the retail banks' break-even condition, given by

$$\max_{\ell_t,\bar{\omega}_{t+1}} \mathbb{E}_t \left(1-\Gamma_{t+1}\right) S_{t+1}\ell_t \quad \text{s.t.} \quad \left(\Gamma_{t+1}-G_{t+1}\right) S_{t+1}\ell_t \geq \left(\ell_t - 1\right), \tag{16}$$

where $S_t \equiv R_{K,t}/R_{t-1}$. The constraint holds for all realizations of $R_{K,t+1}$ because the retail banks' return, R_t, is assumed to be predetermined. The combined first-order condition (substituting out the Lagrange multiplier) is given by

$$\mathbb{E}_t \left(\frac{d\Gamma_{t+1}}{d\Gamma_{t+1} - dG_{t+1}} \right) = \mathbb{E}_t \left(S_{t+1} \left(1 + \frac{\Gamma_{t+1} dG_{t+1} - d\Gamma_{t+1} G_{t+1}}{d\Gamma_{t+1} - dG_{t+1}} \right) \right), \tag{17}$$

where $d\Gamma_t \equiv \partial\Gamma_t/\partial\bar{\omega}_t$ and $dG_t \equiv \partial G_t/\partial\bar{\omega}_t$. The break-even condition from (16) and equation (17) combine to implicitly define a loanable funds supply schedule of the form

$$\mathbb{E}_t S_{t+1} = \theta \left(\underset{+}{\ell_t}, \underset{-}{\lambda_t} \right), \tag{18}$$

where $\mathbb{E}_t S_{t+1}$ is denoted the *illiquidity premium*. The illiquidity premium is increasing in wholesale banks' leverage and decreasing in the intra-period liquidity of capital. Endogenous fluctuations in leverage and exogenous fluctuations in liquidity generate a time-varying wedge between the expected return on capital and the risk-free rate in the economy.

2.5 Closing the model

Aggregation is straightforward since, at the end of a period, wholesale banks are only heterogeneous in net worth but choose a common leverage ratio and face the same interest rate on debt. Wholesale banks' net worth is given by end-of-period profits. A measure, $1-\upsilon$, of wholesale banks are forced to exit and consume their profits while a measure, $1-\upsilon$, of new wholesale banks enter. In addition, all wholesale banks receive a positive but arbitrarily small lump-sum transfer from households. These two assumptions ensure that i) wholesale banks do not accumulate sufficient net worth to no longer need external finance and ii) the net worth of every wholesale bank is positive and the contracting problem is well defined. It follows that the evolution of aggregate net worth, N_t, is given by

$$N_t = \upsilon \left(\left(1-G_t\right) S_t \ell_{t-1} - \left(\ell_{t-1} - 1\right) \right) R_{t-1} N_{t-1}. \tag{19}$$

The deadweight cost of coordination failure is in units of capital: While the aggregate stock of capital purchased in $t-1$ for use in t is K_{t-1}, only $K_t^* = \left(1-G_t\right) K_{t-1}$ is put to productive use. Aggregate wholesale bank consumption of exiting bankers is given by $C_{W,t} = \frac{1-\upsilon}{\upsilon} N_t$. The aggregate resource constraint is given by $Y_t = C_t + C_{W,t} + I_t$. Finally, the two stochastic processes are given by $A_t = A_{t-1}^{\rho_A} e^{\sigma_A \varepsilon_{A,t}}$ and $\lambda_t = \lambda^{1-\rho_\lambda} \lambda_{t-1}^{\rho_\lambda} e^{\sigma_\lambda \varepsilon_{\lambda,t}}$ where $\varepsilon_{A,t}, \varepsilon_{\lambda,t} \sim iid\,(0,1)$.

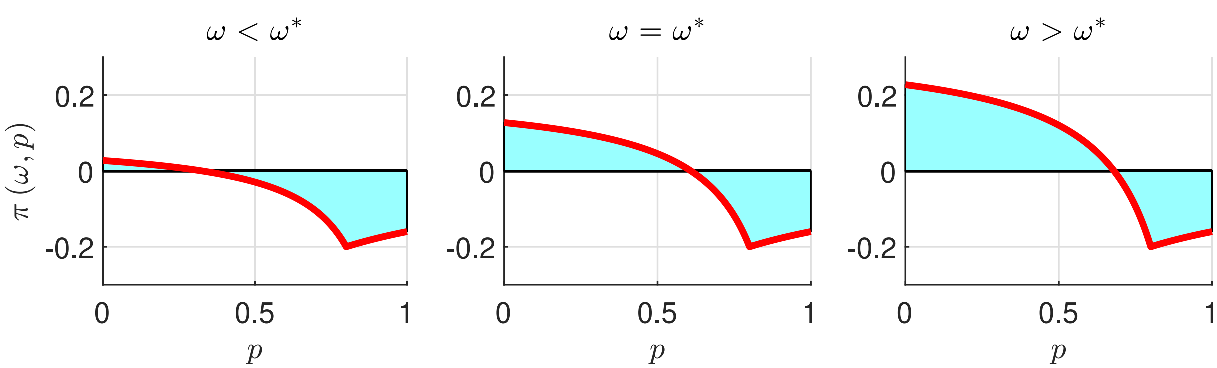
3 Results

3.1 Comparative statics

This section analyzes the comparative static properties of the coordination problem. It shows the interplay between liquidity, leverage, and the illiquidity premium before the full dynamic properties of the model are explored.

In the next subsection, the full model is carefully parameterized to capture moments in US aggregate data. For the present comparative static exercises, the following stylized parameterization is used: $\gamma = \lambda = 0.4$, $\bar{\omega} = 0.5$, and $\sigma^2 = 0.35$, where $\ln(\omega) \sim N\left(-\frac{1}{2}\sigma^2, \sigma^2\right)$. These parameter values aid graphical illustration without altering the qualitative properties of the quantitatively parameterized model presented in the next section.

Figure 1: Net payoff function

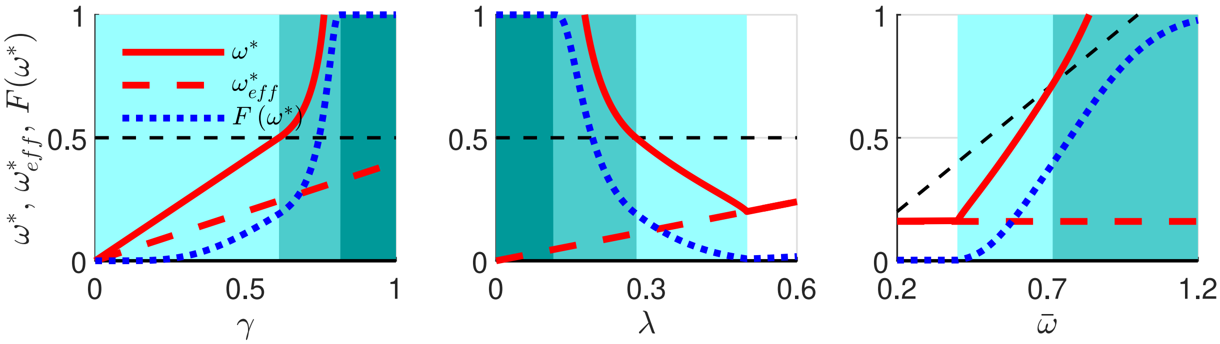


Note: Set $\gamma = \lambda = 0.4$ and $\bar{\omega} = 0.5$. This gives $\omega^* = 0.3275$. The left and right panels set $\omega = \omega^* \pm 0.1$. ω^* is the value of ω that equalized the shaded area above and below the line.

The red line in Figure 1 plots the net payoff function to rolling over for various ω values. The payoff function exhibits two important features: A single crossing where the net payoff to rolling over is zero, and a negative slope, which implies strategic complementarities. In the left-panel (low ω), the equilibrium action is to not rollover whereas in the right-panel (high ω), the equilibrium action is to rollover. The middle panel defines the threshold ω^* (solving the indifference condition in (12)), which is when the sum of the blue areas equals zero.

Figure 2 plots the effect on ω^*, ω^*_{eff} and $F(\omega^*)$ as γ, λ, and $\bar{\omega}$ are altered in the three panels, respectively (holding all else equal). In Section 2, I focused the model's derivation on a

Figure 2: Comparative statics for ω^*, ω^*_{eff}, and $F(\omega^*)$

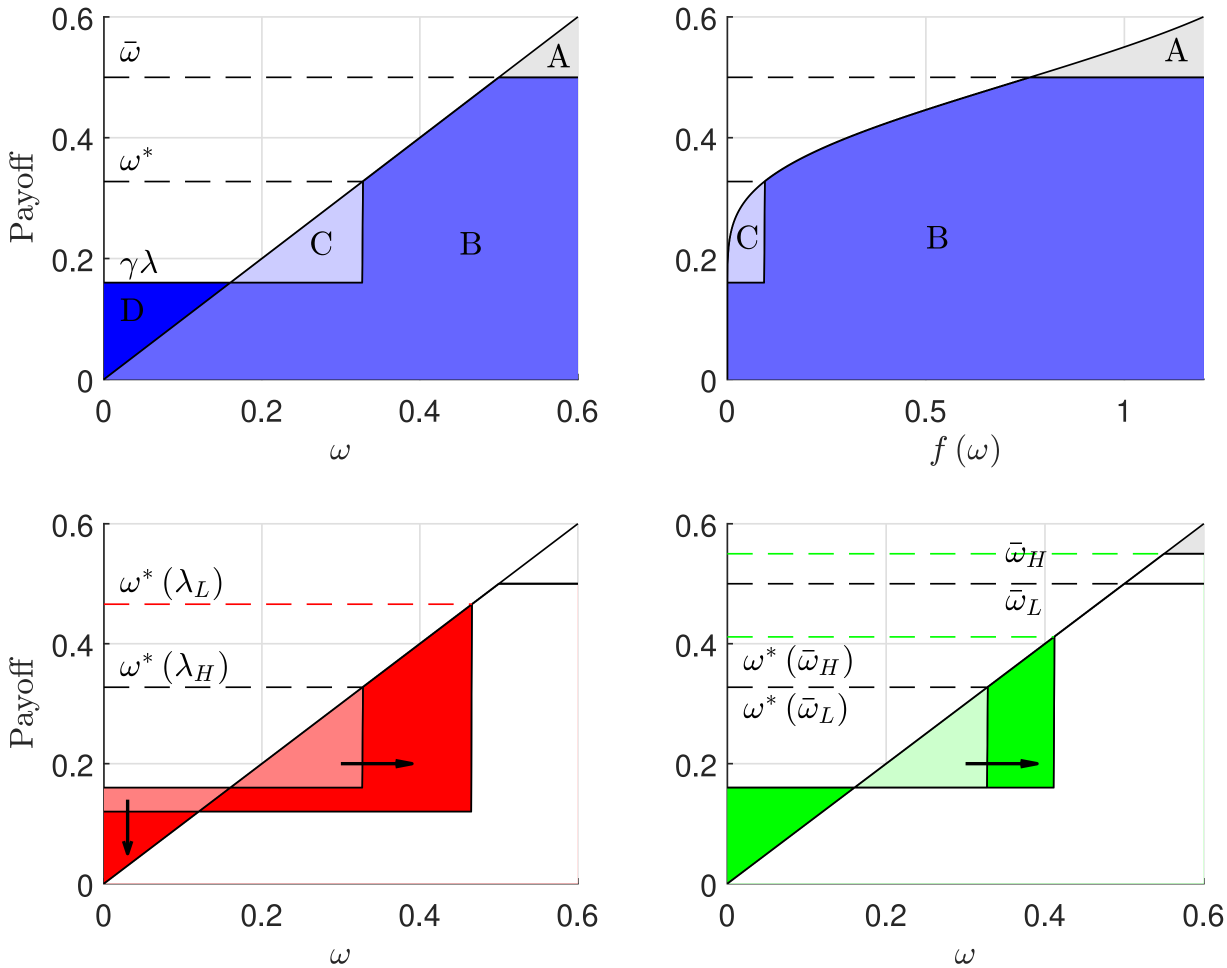


Note: In each panel, γ, λ, and $\bar{\omega}$ are adjusted individually, holding the remainder at the following values: $\gamma = \lambda = 0.4$ and $\bar{\omega} = 0.5$. The shaded areas from white to dark-green represent Scenario 1: No fragility, 2: Mild fragility, 3: Acute fragility, 4: No rollover. The black-dash line indicates $\bar{\omega}$. The intersection of the solid-red and black-dash lines indicates the transition between the Mild and Acute fragility scenario.

specific region of the parameter space, termed "Scenario 2: Mild fragility", that corresponds with the estimated parameterization in Section 3.2 below. However, the entire parameter space admits four types of equilibrium scenario: No fragility; Mild fragility; Acute fragility; and No rollover.[19] These four regions of the parameter space are shown in Figure 2 via the background shading, from white (No fragility) to dark green (No rollover). Focusing on the middle panel, when liquidity is sufficiently high ($\lambda \geq 0.5$, the white region/No fragility scenario), there is no coordination problem. Retail banks base their rollover decisions on their private signals alone and not on higher-order beliefs about other retail banks' actions. When $\lambda \in [0.279, 0.5)$ the economy is in the Mild fragility (pale green) scenario that is the focus of this paper. In this scenario, there is an inefficient incidence of rollover ($\omega^* > \omega^*_{\text{eff}}$). A fall in λ raises the rollover threshold, ω^* (and the fraction of wholesale banks that experience a run, $F(\omega^*)$) and lowers the efficient rollover threshold, thus increasing the inefficiency generated by the coordination problem. When $\lambda \in (0.113, 0.279)$, the economy is in the Acute fragility scenario in which $\omega^* > \bar{\omega}$. In this region, the red line steepens which means that the rollover threshold becomes extremely sensitive to small changes in liquidity. Finally, when $\lambda \leq 0.113$ the liquidity of the capital stock is extremely low, the economy is in the No rollover scenario (dark green region) and $F(\omega^*) = 1$. Clearly, there are interesting nonlinearities in this model, but they are beyond the scope of the current paper to explore further. This paper focuses on perturbations of the model in the light-green (Mild fragility) region. One can think of the model of Gertler and Kiyotaki (2015) and Gertler et al. (2016) as studying large jumps from the white (No fragility) region to the dark-green (No rollover) region.

[19]See the discussion above Table 3 and in Online Appendix A.1 for further details.

Figure 3: Debt contract

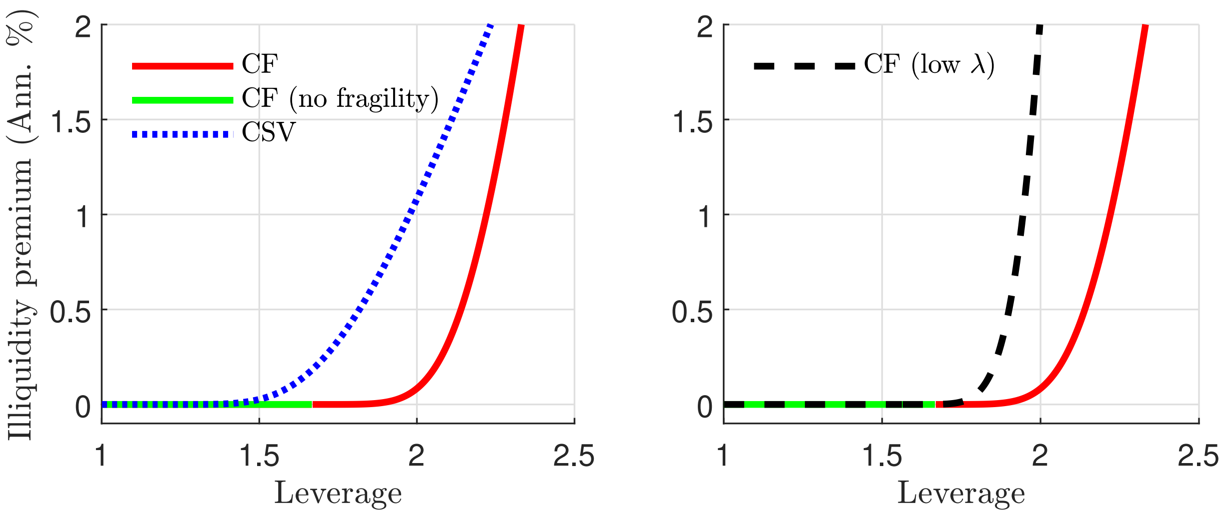


Note: Top-left: $\Gamma(\cdot) = B + C$, $1 - \Gamma(\cdot) = A$, and deadweight cost $G(\cdot) = C - D$. Top-right: Probability-weighted. Bottom-left: Comparative static of a fall in λ from λ_H to λ_L. Deadweight cost rises (area $C - D$ expands). Bottom-right: Comparative static of a rise in $\bar{\omega}$ from $\bar{\omega}_L$ to $\bar{\omega}_H$. Deadweight cost rises.

Figure 3 plots the debt contract, showing how the return on capital is split between the borrower (wholesale bank) and the creditors (retail banks) for different realizations of ω. Top-left panel: A textbook debt contract has the creditor receive the area $\Gamma(\cdot) = B + C$ and the borrower receive the residual $1 - \Gamma(\cdot) = A$. Short-term debt and coordination failure generate a deadweight cost given by $G(\cdot) = C - D$. C captures the gross cost since retail banks would receive a higher return if they could coordinate on rolling over for those realizations of ω. D captures the gross benefit of short-term debt since retail banks receive a higher return for those realizations of ω relative to the case of long-term contracts. Top-right: Plots the same information but scales by $f(\omega)$ rather than ω. It shows that, given the distributional assumptions, area D (the gross benefit of short-term debt) is negligible.

Bottom-left: Shows the effect of a fall in λ from 0.4 to 0.3. The effect is a rise in ω^* and a rise in the deadweight cost (area $C - D$ expands). Bottom-right: Shows the effect of an exogenous rise in the lending rate, with $\bar{\omega}$ rising from 0.5 to 0.55. This also increases ω^* and the deadweight cost of coordination failure.

Figure 4: Illiquidity premium and leverage



Note: $\gamma = \lambda = 0.4$, $\bar{\omega} = 0.5$ and $\sigma = 0.35$. CF denoted coordination failure model. CSV denotes the costly state verification model of Bernanke et al. (1999) with monitoring cost parameter $\mu = 0.166$.

Figure 4 plots the loanable funds supply curve by translating the deadweight costs of coordination failure (CF) studied above into a trade-off between wholesale banks' leverage and the illiquidity premium they pay on external finance. This is done by endogenizing $\bar{\omega}$. The left panel shows that if wholesale banks have low leverage (green line), then there is no coordination problem for retail banks and as a result the illiquidity premium is zero. However, as leverage rises above a critical value then the coordination problem appears (red line), generating an illiquidity premium which is increasing in leverage. An interesting comparison is with an alternative model of financial frictions, the costly state verification (CSV) model of Townsend (1979). In this model, costly state verification generates a *risk* premium even for low levels of leverage but grows more gradually (blue-dot line). The implication of this comparison is that the CSV-type risk premium is larger during normal times (when leverage is relatively low) than the CF-type illiquidity premium. But, in periods of financial stress when borrower net worth falls and leverage sharply rises, the illiquidity premium can rise rapidly and can even become larger than typical risk premia. The right panel shows the effect of a fall in liquidity. When λ falls, the loanable funds supply schedule shifts inward and steepens, resulting in a higher illiquidity premium for a given leverage ratio. The next section studies the dynamic effect of such an illiquidity shock.

3.2 Parameterization

Table 4 lists the parameters values used for the full dynamic model. The model parameters are partitioned into three groups. The first group of parameters are standard values taken from the literature. The second group are calibrated using steady state relationships. The third group are estimated using a simulated method of moments technique.

Table 4: Structural parameters

Standard	α	0.33	β	0.99	δ	0.025	σ_C	2	ρ	3
Calibrated	χ	5.02	υ	0.981	σ^2	0.048	γ	0.589	λ	0.703
Estimated	φ	0.147	σ_a	0.004	ρ_a	0.929	σ_λ	0.004	ρ_λ	0.905

Note: Row 1: Standard values from the literature. Row 2: Calibrated to match first-moments in US data. Row 3: Estimated using simulated method of moments to match second-moments in US data.

Based on standard values in the literature at a quarterly frequency, the capital share of income is $\alpha = 0.33$; the subjective discount factor is $\beta = 0.99$; the depreciation rate of capital is 0.025; the intertemporal elasticity of substitution is $1/\sigma_C = 1/2$; and the Frisch elasticity of labor supply is $1/\rho = 1/3$.

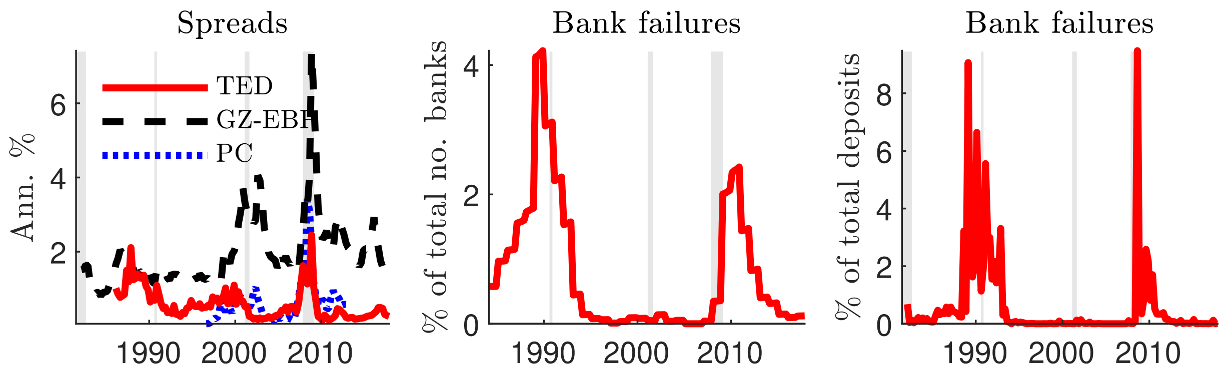
The second set of parameters contains the weight on leisure in the utility function, χ, and the four structural parameters that govern the financial sector: The capital management productivity of retail banks, γ, the steady-state intra-period liquidity of capital, λ, the variance of the distribution of idiosyncratic shocks, σ^2, and the proportion of wholesale banks that survive each period, υ. The values are pinned down by four steady state moments of the model that approximately match long-run averages in US data, given in Table 5.[20]

I use the TED spread—the 3-month Treasury bill rate minus the 3-month LIBOR rate—as a proxy for the illiquidity premium. LIBOR is the rate banks charge each other for lending. Since the coordination problem in the lending relationship between retail and wholesale banks is the only wedge between the return on deposits and the return on capital in the model, the TED spread is a good proxy. For comparison, Figure 5 plots the TED spread alongside the Gilchrist and Zakrajsek (2012) excess bond premium, which is significantly larger but captures a much broader risk premium definition. The figure also plots an alternative measure of the liquidity premium, which takes the principal component of seven spreads series between the return on illiquid assets and Treasuries of similar safety and maturity. This follows the methodology of Bredemeier et al. (2018) (see Online Appendix C.2 for details).[21] I match

[20] χ is chosen such that steady state labor supply is normalized to 1.

[21] Robustness exercises using this series are available on request.

Figure 5: Illiquidity premium and bank failure



Note: TED is the spread between 3-month LIBOR and the 3-month Treasury bill. GZ-EBP is the Gilchrist and Zakrajsek (2012) excess bond premium. PC is a liquidity premium calculated from 7 spread series using principal components analysis following Bredemeier et al. (2018). Bank failure source: FDIC. Shaded areas denote NBER recessions.

the steady state illiquidity premium to the mean of the TED spread from 1986-2017, which is 58bp.

Figure 5 also plots a time-series of bank failures, which are constructed from FDIC data. The series goes back to 1934 but for consistency with the other time-series, I use only the period 1986-2017. In the model, the fraction of banks that fail and the fraction of failures weighted by balance sheet size are equivalent. In the data, however, these series are quite different. In particular, at the peak of the 2007-08 financial crisis, 2% of banks covered by the FDIC failed but this accounted for 9% of total deposits. In addition, there were a large number of bank failures in the aftermath of the crisis in 2010-12 but these were mainly small banks. Thus, the series for bank failures in terms of total deposits appears much less persistent. For the empirical exercise, I use the measure of bank failures as a share of total deposits (right-panel). I match the mean annualized failure rate of 0.67% for 1986-2017.

Leverage in the wholesale bank sector varies widely across financial institutions, with some banks with leverage in excess of 10. I take a conservative estimate and calibrate the steady state leverage of the wholesale bank sector to be 4 following Gertler et al. (2012).[22] Finally, the average recovery ratio of liquidated assets is set at 50% following estimates from Berger et al. (1996).

Following the method of simulated moments in Basu and Bundick (2017), the third group of parameters are estimated. These parameters are chosen to minimize the distance

[22] While the deterministic steady state is, by definition, independent of uncertainty, it is likely that wholesale banks' (privately) optimal leverage is dependent on the risk they face on their balance sheet. Gertler et al. (2012) and de Groot (2014) investigate how leverage at the *risk-adjusted* steady state can rise (and hence amplify the financial accelerator) in a low risk environment.

Table 5: Targeted steady state moments

Moment	Description	Value
$R_K - R$	Illiquidity premium†	58bp (ann.)
$F(\bar{\omega})$	Bank failure rate††	0.67% (ann.)
K/N	Capital-to-net worth ratio	4‡
$\int_0^{\omega^*} \frac{\gamma\lambda}{\omega} f(\omega)\, d\omega$	Average recovery ratio of liquidated assets	50%‡‡

Note: † TED spread; †† source: FDIC; ‡ Gertler et al. (2012). ‡‡ Berger et al. (1996).

between model moments and second-moments in US aggregate time-series data. Formally, the estimator is the solution of the following problem

$$J = \min_{\theta} \left(M^D - M(\theta) \right)' W^{-1} \left(M^D - M(\theta) \right), \tag{20}$$

where M^D is a vector of data moments; $M(\theta)$ denotes its model counterpart; θ is the vector of parameters to be estimated; and W is a diagonal matrix containing the standard errors of the estimated data moments.

The estimation targets ten moments from aggregate US time-series data: The standard deviation and autocorrelation of output, consumption, investment, hours, and the illiquidity premium. Five parameters are estimated, $\theta = \{\varphi, \sigma_a, \rho_a, \sigma_\lambda, \rho_\lambda\}$, four of which are the persistence and standard deviation of the two exogenous shock series: Technology, A_t, and liquidity, λ_t. The final parameter, φ, controls investment-adjustments costs. This is a key parameter for determining the strength of the financial accelerator. When φ is zero, the financial accelerator is generally weak because investment demand adjusts rapidly to changes in financial conditions.[23]

Table 6 reports the success of the model in matching business cycle moments. Given the parsimony of the model, it does a reasonable job. Most notably, investment is not volatile enough and consumption is too persistent. Table 6 also reports two untargeted moments related to the cross-correlation between GDP and the TED spread. The data suggests that GDP lags the TED spread, whereas in the model the contemporaneous cross-correlation is stronger. Online Appendix B.2 reports robustness results when these two moments are targeted in the estimation. Enriching the model with habits in consumption would help

[23] The model is solved to first-order in the neighborhood of the deterministic steady state. The model, however, admits interesting nonlinearities as shown in Section 3. Although it would be a fruitful avenue for future research to solve the model using global methods, it is beyond the scope of the current paper.

improve the model fit along this dimension.

Table 6: Business cycle moments

Moment	Data	Model	Moment	Data	Model
Targeted moments					
std(GDP)	1.529	1.651	ac(GDP)	0.859	0.930
std(C)	1.163	1.158	ac(C)	0.785	0.990
std(I)	4.784	3.640	ac(I)	0.901	0.851
std(Hours)	0.518	0.549	ac(Hours)	0.804	0.781
std(TED)	0.236	0.130	ac(TED)	0.889	0.644
Untargeted moments					
corr(GDP$_t$,TED$_t$)	−0.304	−0.601	corr(GDP$_t$,TED$_{t-4}$)	−0.489	−0.444

Note: Construction of data moments given in Online Appendix C.4.

3.3 Impulse responses and crisis scenario

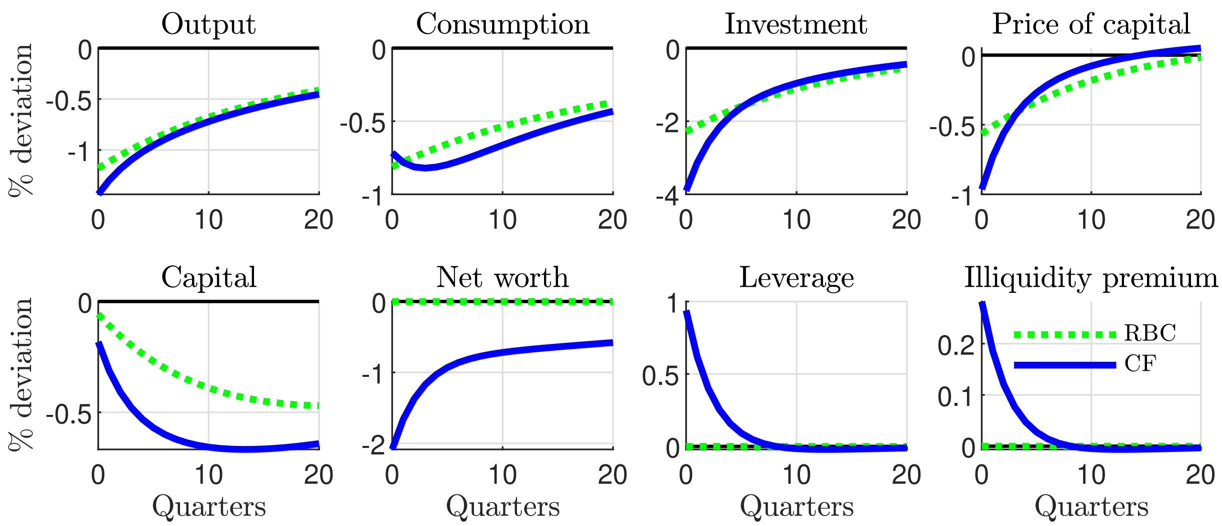
Technology shocks Figure 6 shows the reaction to a 1% negative technology shock.[24] The blue-solid and green-dot lines show the reaction of the model with and without coordination failure, respectively. Coordination failure does not significantly alter the qualitative shapes of the responses, but does alter the magnitude of the responses. Notably, the drops in investment, asset prices and the capital stock are magnified.

Coordination failure introduces three new aggregate variables of interest: Wholesale bank net worth, leverage, and illiquidity premium. The negative technology shock causes a drop in net worth and an increase in leverage. The risk-free (deposit) rate falls while the expected return on capital rises, leading to a sharp rise in the illiquidity premium.[25] These responses are the result of three features of coordination failure. First, the interest rate on wholesale bank debt is a function of the return on capital, which means that wholesale banks absorb the aggregate risk. When the negative technology shock hits, the realized return on

[24]Supplementary material on capital quality and net worth shocks and the behaviour of the rollover threshold, recovery, default, and rollover rates are available on request.

[25]Countercyclical leverage is a feature of most financial accelerator models. Adrian et al. (2013) criticize these models because leverage is procyclical in US data. However, Gertler (2013) argues the discrepancy is due to differences in net worth measurement. In the model, net worth is measured with market values. In contrast, equity in the data is measured using a mixture of book and fair value accounting and during periods of market illiquidity fair value accounting replaces market values with “smoothed” values.

Figure 6: Technology shock



Note: 1% negative technology shock. CF denotes the full coordination failure model. RBC denotes the model without coordination failure.

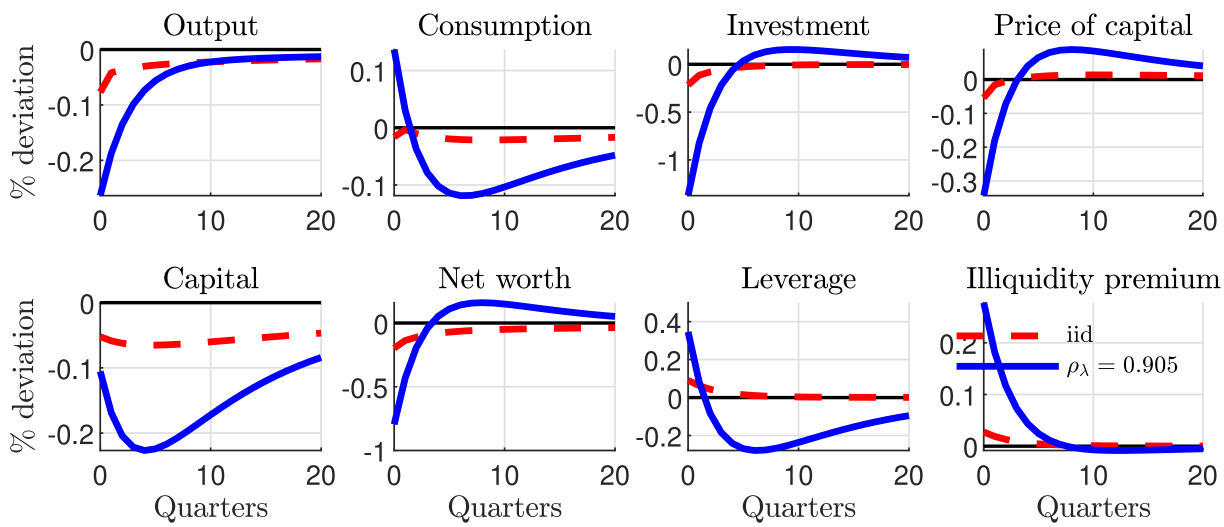
capital is below its expected return, which drives down wholesale bank profits and net worth. Second, wholesale bank net worth decreases faster than the demand for capital, implicitly causing leverage to rise. Third, higher leverage increases the severity of the coordination problem among retail banks, causing the illiquidity premium to rise. As a result, retail banks demand a higher interest rate on wholesale bank debt (i.e. an increase in $\bar{\omega}_t$) following a negative productivity shock, which increases the illiquidity of wholesale banks yet further. This causes investment and the price of capital to fall further in response to a negative technology shock. Investment falls 3.9% on impact following a 1% technology shock in the coordination failure model, relative to a 2.1% in the frictionless case.

Illiquidity shock A novel feature of the model is the ability to generate an exogenous rise in illiquidity in credit markets. Figure 7 shows the response to a 1% rise in intra-period capital illiquidity with an iid (red-dash) and a persistent shock (blue-solid line), respectively.

A rise in the illiquidity of capital leads to a rise in the rollover threshold, ω^*, implying a higher incidence of bank runs. This causes a sharp increase in the illiquidity premium paid by wholesale banks on external finance, with a rise in the expected return on capital and a fall in the deposit rate. Retail banks reduce the supply of loanable funds. However, the drop in the demand for capital is insufficient to offset the fall in wholesale bank net worth. To break-even, retail banks lower the return on deposits. Households, facing a lower return on savings, generate a temporary consumption boom.[26] In the transition back to steady state,

[26]The illiquidity shock causes consumption to rise temporarily while output and investment fall. This is

Figure 7: Illiquidity shock



Note: 1% illiquidity shock

the fall in the demand for investment causes a decline in the capital stock. As the impact of the illiquidity shock recedes, households cut consumption to restore their steady state savings ratio, requiring a long period of deleveraging by wholesale banks.

The size and persistence in the response of capital (and hence output) is sensitive to the persistence of the exogenous rise in illiquidity. The evolution of capital is relatively gradual. A less persistent shock, therefore, gives less opportunity for capital to fall and do serious damage to potential output. Thus, the length and severity of a recession depends on how long the credit market remains illiquid.

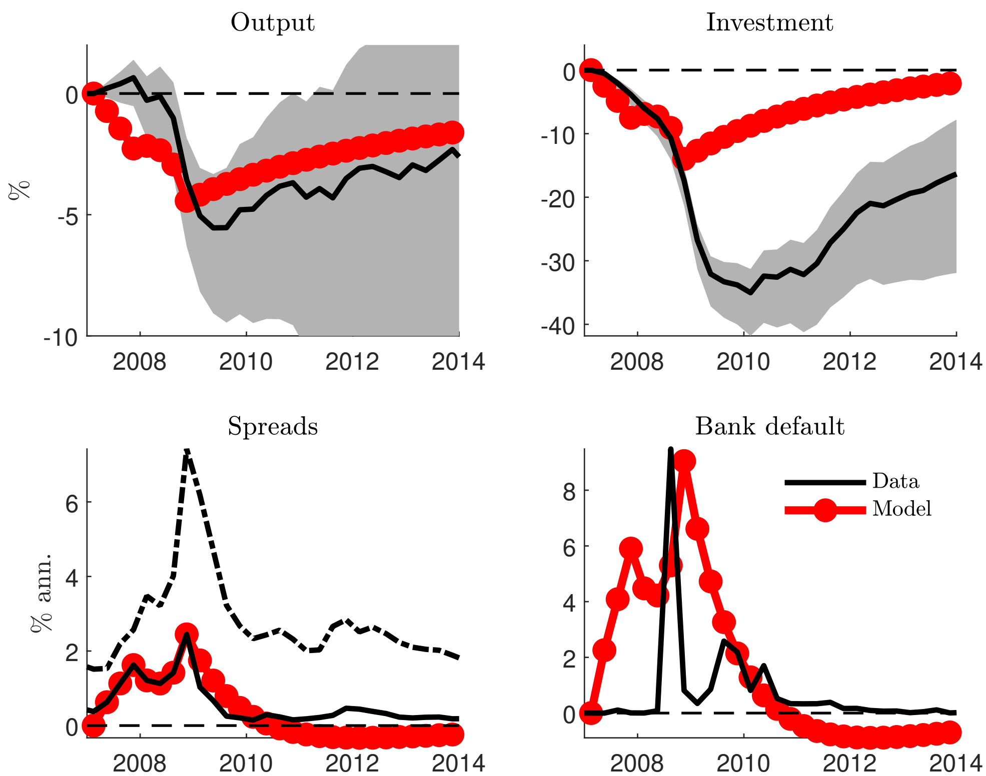
This model has several features unique to coordination failure. First, retail banks are least likely to rollover debt when liquidity is most needed. Second, as the constraints on wholesale banks tighten countercyclically, the share of capital held by retail banks will move countercyclically. This occurred during the financial crisis with dealer banks in the shadow banking sector shrinking and commercial banks expanding their market share.

Illiquidity during the 2007-08 financial crisis This section provides an illiquidity shock narrative of the 2007-08 financial crisis as an external validation exercise for the model. Since the model is a parsimonious RBC model, chosen for clarity rather than quantitative accuracy, it is unlikely to provide a precise fit to the data. However, the exercise provides a good way of assessing its strengths and weaknesses. In the exercise, I assume the economy is

because of households' intertemporal elasticity of substitution, with the substitution effect dominating the wealth effect. This result is shared by many other models that have shocks to preferences, investment goods prices or financial frictions. To alleviate this result, one can correlate technology and illiquidity shocks. Indeed, during recessions, markets experience more illiquidity.

hit by a sequence of illiquidity shocks from 2007q2–2008q4 that match the evolution of the illiquidity premium (TED spread) in the data. Using simple projection methods, I estimate a distribution of counterfactual paths for output, investment, the illiquidity premium and bank failure had the financial crisis not occurred. The black line in Figure 8 represents the deviation between the actual path for these variables and the median of the counterfactual path. The methodology follows Christiano et al. (2015) and is described in Online Appendix C.5. The grey area captures the uncertainty of the counterfactual paths. The counterfactual evolution of output is most uncertain while the bank default is estimated very precisely (i.e. without the financial crisis, bank default would have almost certainly remained at zero).

Figure 8: Illiquidity shocks during the 2007-08 crisis



Note: Black line represent the data relative to an uncertain trend following Christiano et al. (2015). Black-dash is the Gilchrist and Zakrajsek (2012) EBP. Red is the model prediction with illiquidity shocks chosen to exactly match the TED spread from 2007q2–2008q4.

The model's illiquidity shocks capture well the fall in output during the financial crisis but captures less than half the drop in investment, suggesting that investment specific shocks also played an important role. The model captures accurately the peak bank failure rate of 9%. However, the model predicts that bank failures would have appeared as early as 2007 and would have persisted into 2010. Thus, when integrating over the total number of bank failures for the 2007-2010 period, the model overpredicts the number of bank failures. Of course, there is a clear rationale for policy (monetary or fiscal) to offset the effect of illiquidity in the credit market, and this is addressed in the next section.

4 Policy responses

The coordination failure model facilitates the analysis of two *unconventional* credit market policies adopted by the US Federal Reserve during the 2007-08 financial crisis: 1) Direct lending (or *liquidity injections*) in credit markets and 2) equity injections.[27]

4.1 Direct lending (DL)

In this intervention, the policymaker supplements private lending in credit markets by directly lending to wholesale banks when the illiquidity premium is high. Since wholesale banks in the model are funded by a continuum of retail banks, the retail banks cannot coordinate actions. The policymaker instead behaves as a single, large market participant with deep pockets. By committing to rollover, it is able to reduce the coordination problem.[28]

Let $\mathtt{n}_t$ denote the proportion of total lending to wholesale bank w provided by retail banks. Funding provided by the policymaker is therefore given by $(1 - \mathtt{n}_t)(Q_t K_{wt} - N_{wt})$. Retail banks can still choose not to rollover while the policymaker is assumed to always rollover.[29] The policymaker lends at the prevailing market rate $R_{L,t}$. However, by expanding the supply of run-free funds available in the market, it reduces the interest rate on wholesale bank debt endogenously. The rollover threshold, augmented by direct lending, is given by

$$\omega^* = \gamma\lambda\mathtt{n}x\,(1 - \ln(x)) \,/\, (\mathtt{n}x + (1 - \mathtt{n}x)\ln(1 - \mathtt{n}x))\,, \tag{21}$$

where $x \equiv \lambda / (\mathtt{n}\bar{\omega})$ is the new measure of endogenous illiquidity. The efficient rollover threshold becomes $\omega^*_{\text{eff}} = \gamma\lambda/\mathtt{n}$. All else equal, direct lending decreases ω^* and increases the efficient threshold, thus reducing the market distortion.[30] Retail banks' break-even condition is un-

[27] Cúrdia and Woodford (2010), Reis (2009a) and Gertler and Kiyotaki (2010) study the effect of similar credit market policies.

[28] In other respects, the government is likely less efficient at intermediating funds than the private sector. Thus, think of this as an intervention in crisis times only.

[29] In the crisis, the Fed lengthened the maturity of banks' borrowing by directly lending at longer maturities than private creditors. Fed press release: `http://www.federalreserve.gov/newsevents/press/monetary/20081007c.htm`

[30] A sufficiently large intervention will push the economy into the "No fragility" region (see Online Appendix A.1).

changed except for the deadweight cost, G_t, given by

$$G = \int_0^{\omega^*} (\omega - \gamma\lambda/\mathtt{n})\, f(\omega)\, d\omega. \tag{22}$$

4.2 Equity injections (EI)

In this intervention, the policymaker acquires part ownership of wholesale banks.[31] I assume that government and private equity have the same characteristics. Let $\mathtt{c}_t$ be the proportion of total equity that is privately held by wholesale bankers, such that the funds injected by the government are given by $(1-\mathtt{c}_t)\, N_t$. The retail banks' break-even condition is unchanged but wholesale bank profits are split between the wholesale bankers and the government in proportion to $\mathtt{c}_t$. The augment net worth equation is given by

$$N_t = \frac{\mathtt{c}_{t-1}}{\mathtt{c}_t} \upsilon \left((1-G_t)\, S_t \ell_{t-1} - (\ell_{t-1} - 1) \right) R_{t-1} N_{t-1}.$$

Since equity injections expand wholesale bank net worth, this will expand credit creation, reduce leverage, and lower the illiquidity premium.

4.3 The policy rule

The policymaker obtains funds by levying lump sum taxes and returns from its policy interventions are transferred lump sum back to households. The government runs a balanced budget.[32] The aim is to assess the relative power of the two alternative instruments and this simplification allows a clean comparison. The government flow budget constraint is given by

$$\begin{aligned} T_t = & \underbrace{(1-\mathtt{n}_{t-1}) \left(\Gamma_t - \int_0^{\omega_t^*} \omega f(\omega)\, d\omega \right) R_{K,t} Q_{t-1} K_{t-1}}_{\text{Return on direct lending}} \\ & + \underbrace{(1-\mathtt{c}_{t-1})(1-\Gamma_t)\, R_{K,t} Q_{t-1} K_{t-1}}_{\text{Return on equity injections}} - \underbrace{(1-\mathtt{n}_t)(Q_t K_t - N_t)}_{\text{Direct lending}} - \underbrace{(1-\mathtt{c}_t)\, N_t}_{\text{Equity injections}}, \end{aligned} \tag{23}$$

where T_t are transfers net of taxes. Note the government does not receive the same return on direct lending as retail banks. Since the policymaker commits to always rollover, the government earns zero whereas retail banks earn $\gamma\lambda_t$ when a run occurs. I assume that the policymaker's two instruments, $\mathtt{c}_t$ and $\mathtt{n}_t$ are governed by a simple implementable policy rule

[31] I abstract from efficiency costs associated with government acquisition of equity.

[32] The lump sum taxes/transfers should more realistically be modelled as central bank reserves when comparing to developments during the financial crisis. However, the additional realism adds unnecessary complexity to the model without materially altering the comparison of the policy instruments.

given by

$$\mathtt{n}_t = 1 - a_{DL}\left(\mathbb{E}_t S_{t+1}/S - 1\right) \quad \text{and} \quad \mathtt{c}_t = 1 - a_{EI}\left(\mathbb{E}_t S_{t+1}/S - 1\right), \tag{24}$$

where $a_{DL}, a_{EI} \geq 0$. Thus, the size of the policy intervention depends positively on the illiquidity premium. The rule is reasonable since the magnitude of the distortion the policymaker is trying to offset is proxied by the illiquidity premium. The rule is also practically implementable since credit spreads are observable (although disentangling illiquidity risk from credit risk may not be so easy). After all, it was the sharp rise in spreads during the financial crisis that pushed the Fed into introducing unconventional credit policies, even before the conventional tool of monetary policy, the nominal interest rate, reached the zero lower bound.

4.4 Illiquidity shock with policy responses

Figure 9 shows a 1% fall in the intra-period liquidity of the capital stock. To provide a clear comparison between policy instruments, the experiment ensures that both policies deliver the same initial cost to the government in terms of GDP. This requires the parameters of the policy rules to be set at $a_{DL} = 3.00$ and $a_{EI} = 14.02$.[33]

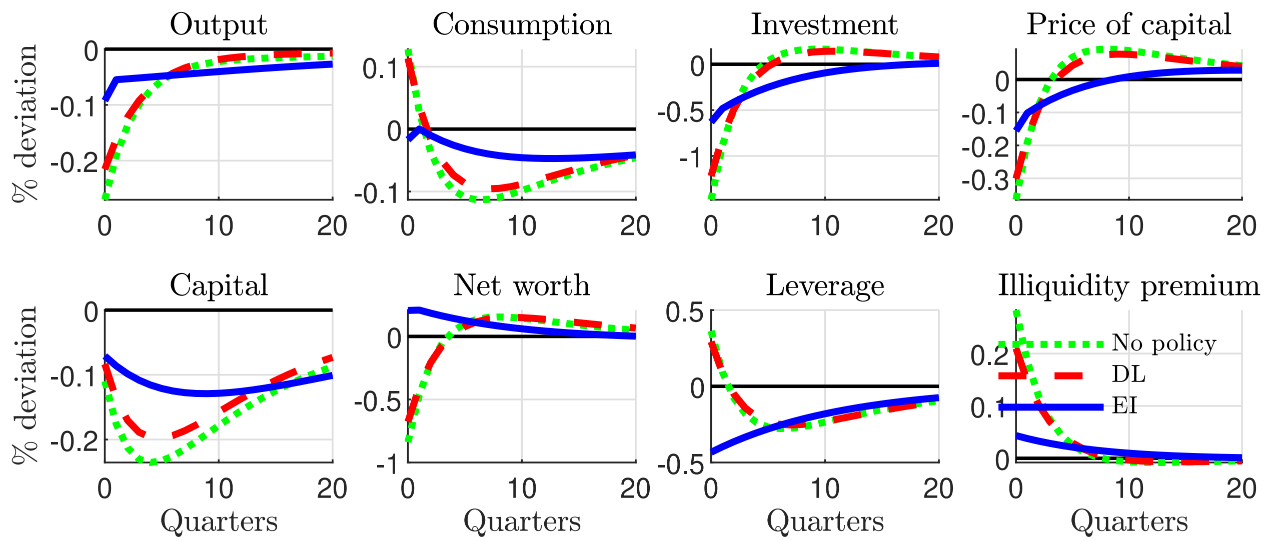
Figure 9 shows that equity injections mitigate the effects of the initial shock to liquidity better than direct lending. The initial fall in output with no policy intervention was 0.27%. Equity injections and direct lending reduced this to 0.09% and 0.22%, respectively. The reason is that equity injections directly offset the fall in net worth, actually causing leverage to fall. However, while equity injections reduce the initial impact of the illiquidity shock, they also cause the effects of the shock to persist for longer. The reason is—without coordination problems, the Modigliani-Miller theorem states the irrelevance between debt or equity financing. But, with coordination problems, the shadow price of equity is lower, exactly because equity avoids the coordination problem. Wholesale banks build up equity so that they don't require debt finance. Direct lending reduces the maturity mismatch but does not materially improve the solvency of wholesale banks. Equity injections are therefore powerful in mitigating the problem in credit markets (because it lowers the need to access them). However, as the illiquidity premium recedes, the policymaker's withdrawal of equity offsets the recovery in net worth that the wholesale bank would have experienced in the counterfactual scenario without policy intervention.

As a result of the additional persistence, the present discounted value of equity injections is actually larger than the present discounted value of direct lending. Online Appendix B.3

[33] In terms of quantities, the size of the initial intervention in these experiments is 0.6% of annual GDP, or for the US economy, approximately \$90bn. The Fed's balance sheet expanded by \$1tn during the crisis.

reruns the simulation with $a_{AI} = 3.44$ such that the present discounted value, rather that the initial cost, is equalized. In this case, equity injections still reduce the illiquidity premium and output drop on impact more than direct lending, although by less.

Figure 9: Illiquidity shock and policy response



Note: 1% illiquidity shock with policy intervention

5 Conclusion

This paper incorporates short-term uncoordinated creditors in credit markets in a dynamic, general equilibrium setting. The coordination problem generates a time-varying incidence of bank runs, rising during downturns and especially during periods of illiquidity. The resulting illiquidity premium provides a new lens through which to study the financial accelerator and the role of credit market interventions during financial crises. In particular, the model shows that equity injections are more powerful policies than direct lending.

Moreover, the microfounded coordination problem at the heart of this model provides rich nonlinearities that this current research has not yet fully explored and will likely be a fruitful avenue for future research.

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