

Interbank Networks in the Shadows of the Federal Reserve Act*

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Abstract

We study how the provision of public liquidity affects the role and structure of the banking system by analyzing the change of portfolios and interbank relationships of nonmember (“shadow”) banks upon the creation of the U.S. Federal Reserve. Using unique data on the payments and funding networks of Virginia state banks, we document that the funding role of the interbank system became more important, and its payments role less important. In addition, interbank relationships became less centralized. Based on these findings, we develop a model to assess how public liquidity provision affects banking stability.

Keywords: Dual Banking System, Federal Reserve Act, Shadow Banks, Interbank Networks, Systemic Risk

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1 Introduction

The Federal Reserve System and other central banks in the world infused large amounts of liquidity in recent years, most notably during the 2008 financial crisis, the 2012 Eurozone sovereign debt crisis and the 2020 COVID-19 pandemic. These policies, which were introduced to stabilize financial markets, prompted calls to impose more stringent regulations on financial intermediaries with direct access to public liquidity. The provision of public liquidity, however, may affect the behavior of intermediaries with direct access and, but through interbank networks also intermediaries without direct access. How does public liquidity affect the operations and interactions between these different financial intermediaries? What is the ultimate effect on financial stability?

Answering these questions is challenging. One obstacle is the ubiquitous presence of central banking in the world, which prevents a direct comparison of interbank networks with and without public liquidity provision. Another obstacle is the complexity of modern financial markets, which makes it difficult to document changes in interbank networks in response to changes in central bank policies. A third obstacle is identifying banks' expectations about central bank policies under different circumstances and shocks. Answering these questions is more difficult for unregulated financial intermediaries without direct access to public liquidity.

In this paper, we tackle these challenges by studying the banking network before and after the introduction of the Federal Reserve System (the Fed) in 1913. The Fed was introduced to offer liquidity to member banks through a discount window, imposing stricter regulations as a precondition. The Act made membership compulsory for national banks but voluntary for state banks, under the presumption that most state banks would choose to join. However, most of them did not because nonmembers could still access public liquidity indirectly through member banks while avoiding the more stringent regulations (see evidence on Anderson et al. (2018) and Carlson and Wheelock (2018a)). Hence, the Federal Reserve Act may have created what we now call a *shadow banking system*: a system of banks operating without direct access to liquidity facilities or bailout promises and with less stringent supervision.

Despite the importance of nonmember banks in the banking system (70% of all banks) and their reliance on member banks, not much is known about the operation and structure of their interbank relationships. To make progress on this dimension, we construct a dataset of state banks in Virginia from state examination reports for the years 1911 and 1922 (that is, before and after the passage of the Federal Reserve Act). These examination reports provide detailed information of banks' assets, liabilities and counterparties. On the asset side, we observe cash holdings, deposits (in other banks), bonds and loans. On the liability side, we observe equity, deposits (from households and from other banks) and short-term borrowing (from other

banks). We collect information on interbank relationships disaggregated by the respondent and correspondent of each bank.¹ On interbank relationships, we document their *payments role* (amount of deposits due from each correspondent and the name of such correspondent) and their *funding role* (amount of short-term borrowing from each correspondent and the name of such correspondent). To the best of our knowledge this is the first dataset that provides a *complete* picture of state/nonmember banks' *payments and funding networks*. Even though it restricts to Virginia, our data contrast to existing studies that only report the total amounts of interbank items, not disaggregated by individual correspondent bank, or use correspondent links without knowing the function and strength of those relations.²

We show that the role of the interbank system changed after the founding of the Fed; the funding role of became more important, while the payments role became less important. Before the introduction of the Fed, banks managed liquidity both through interbank deposits and short-term borrowing, but after its creation nonmember banks borrowed more intensively from member banks and reduced the volume of deposits that they maintained in their correspondents, especially in financial center banks. This behavior was strikingly similar to that of member banks (as documented by Carlson and Wheelock (2018a)) even though nonmembers did not have direct access to the Fed's discount window and they were not subject to the regulation that prohibited the use of correspondent deposits to meet reserve requirements.³

We further show that the structure of the interbank system also changed after the creation of the Fed. The network became less centralized, with banks reducing their connectivity to financial centers. Before the founding of the Fed, both the payment and funding relationships were concentrated in financial center banks. While payments relationships were concentrated in national financial centers (e.g. New York), the funding relationships were concentrated in local financial centers (e.g. Richmond). The payments role was centralized in national financial centers, such as New York City, because banks provided private liquidity against regional liquidity shocks and smoothed interregional flows by pooling interbank deposits from different regions (Carlson and Wheelock (2018a)). The funding network was more local

¹Banks placing deposits in other banks were called respondents and banks receiving deposits were called correspondents. Correspondent banks were generally located in financial centers.

²Commercial bank directories such as *Rand McNally* and *Polk*, for instance, provide information on self-reported correspondent linkages (and sometimes the names of counterparties), but not the types of interbank transactions nor the amounts associated with these transactions. Further, while several studies have examined how interbank deposits contributed to financial contagion, only recently attention has been paid to the role of interbank borrowing, such as Lockhart (1921a), Lockhart (1921b), Calomiris and Carlson (2014), and Redenius and Weiman (2020).

³We do not formally test whether the Fed caused or contributed to changes in nonmember banks' balance sheets and network structure, but we provide evidence on *nonmember banks* that is consistent with prior research focusing on *member banks*, such as Carlson and Wheelock (2018b), Carlson and Wheelock (2018a), and Jaremski and Wheelock (2020).

because rural banks borrowed from banks close in proximity when they could not withdraw interbank deposits. (Redenius and Weiman (2011)). After the founding of the Fed, both payments and funding relationships became even more local. This change was mostly driven by nonmember banks entering the market after the Fed's creation, since nonmember banks existing before the Fed did not sever (at the extensive margin) their previous relationships with correspondents in financial centers.

The changes in the role and structure of the interbank system can affect financial stability due to counterparty risk. Nonmember banks borrowing short term loans from members with access to public liquidity could pose a major threat for nonmembers if members cut back short-term loans. Similarly, interbank deposits in member banks could create a threat for members if nonmember banks withdraw in excess and drain member banks' liquidity.

To understand how these changes would have affected the stability of the banking system, we construct an endogenous interbank network model with individual banks' portfolio choices. The model is useful for two reasons. First, we show that the observed changes in the interbank system are consistent with its role in providing *insurance by diversification*, with public liquidity provision weakening this role. Second, by distinguishing between payments and funding roles of the interbank system, we can provide insights on how public liquidity provision affected financial stability through its impact on banks' portfolios and the interbank network structure between members and nonmembers.

In the model, the bank faces liquidity shocks in the form of deposit withdrawals. Given these shocks, and in the absence of public liquidity, the bank follows two strategies. First, it allocates assets in the following pecking order: loans, interbank deposits, and cash. When the bank faces a larger likelihood of withdrawals, and to prevent costly liquidations, it chooses to hold fewer loans and more interbank deposits and cash. Second, the bank accesses other banks' idle liquidity through well connected counterparties. The first motive generates a *payment network* under which the bank may forego financing productive loans in order to hold deposits in other banks to face potential withdrawals. The second motive generates a *core-periphery network*, with the most connected banks located at the core (such as New York) as a hub to insure shocks across regions. This is consistent with a branch of literature, such as Allen and Gale (2000) and Freixas et al. (2000), that claims that a connected network has the function of providing liquidity insurance against exogenous shocks to individual banks. We extend this framework by endogenizing the individual portfolio and connection choices.

Once public liquidity is introduced (in our application, through the creation of the Federal Reserve System), the role and structure of the interbank system changes for two reasons. First, its role changes because insurance needs against withdrawal shocks, both by member

and nonmember banks, depend less on diversification and more on borrowing public liquidity (either directly from the Fed or indirectly through member banks). Having access to public liquidity allows banks to easily address liquidity shocks by borrowing, without the need to hold so much cash and interbank deposits and the chance of investing more in illiquid assets. This change in bank portfolios altered the interbank system from a *payment network* to a *funding network*, from a *tool for diversification* to a *pipeline to public funds*. This result is consistent with the changes in portfolios that we documented for nonmember banks in Virginia after the creation of the Federal Reserve. Second, the introduction of public liquidity reduces the banks’ need to hedge against local liquidity shocks by obtaining liquidity through their counterparties in other regions. As a response, banks increased their reliance on local member correspondents (cheaper due to shorter distances, better information, stronger relations, etc.), changing the structure of the interbank network towards less exposure to a financial core, *crowding out private inter-regional insurance*. In short, financial center banks transformed from being a *provider of private liquidity insurance* to a *conduit for public liquidity insurance*. This result is again consistent with nonmember Virginia banks having “more local” counterparties after the Federal Reserve was created.

The provision of public liquidity made the overall network more resilient to idiosyncratic shocks but more vulnerable to systemic shocks. Under normal circumstances, public liquidity prevents banks from costly asset liquidations when they are subject to withdrawal shocks. However, the endogenous reaction of banks magnifies vulnerability that is larger than what the system would experience without the promise of public liquidity, as more risks would accumulate within banks and within regions.

The danger of having a large number of banks operating outside the Federal Reserve System has been well recognized. While previous research primarily considers how this “shadow” system constrains monetary policy or crises management, we highlight the endogenous reaction of nonmembers in terms of their portfolio choices and their connectivity to other banks, particularly those under the purview of the Fed, which puts the whole system in a more vulnerable position, possibly at a social cost.⁴ Our study, hence, has implications for policy today. Central bank policies affect all financial institutions, and giving access to public liquidity without regulating the whole financial network may have adverse consequences by accumulating systemic risk in parts of the network that are connected but not monitored. As a result, the financial system may ultimately require central bank interventions that are larger than expected.⁵

⁴Some studies have shown that the inability of nonmember banks to access central bank liquidity magnified the severity of the Great Depression, leading to the creation of new and more extensive lending facilities, such as the Reconstruction Finance Corporation (Wicker (2000), Anbil and Vossmeier (2017)).

⁵We focus on providing positive implications of public liquidity provision in terms of a trade-off between

Related Literature: Our paper contributes to the literature that examines how the founding of the Fed affected the banking system. Previous studies have focused on member banks and found that the Fed’s founding was accompanied by a large decline in the average volume of their interbank deposits, enabling them to operate with less liquid buffers (Anderson et al. (2018), Carlson and Wheelock (2018b), Carlson and Wheelock (2018a)). These studies highlight the emergence of new systemic risk because a reduction in cash holdings made the banking system less resilient to liquidity shocks, which in turn increased the likelihood of member banks to turn to the Fed for assistance. We highlight that this fragility extended to nonmembers in spite of their lack of direct access to public liquidity, magnifying further the emergence of systemic risk given by their less stringent regulations.

Other studies focus on the structural changes of *interbank deposit networks* upon the Federal Reserve Act, using correspondent linkage information from *Rand McNally Directory* (Jaremski and Wheelock (2020), Das et al. (2018)). These studies cannot distinguish between payments and funding networks, nor can they examine the amount of transactions at the intensive margin. Instead, we examine both the *payments role* (deposits) and *funding role* (short-term borrowing) of interbank relationships and the strength of these relationships.

Our paper also contributes to the recent literature on the rise of the modern shadow banking through both regulatory arbitrage, such as Ordonez (2018), and scarce public liquidity provision, such as Bengui et al. (2019). We show that these two factors were also present during the growth of perhaps the first shadow banking system in the U.S. The modern application of our insights also contribute to the recent literature on the transmission of monetary policy through the shadow banking sector (Adrian and Shin (2009), Freixas et al. (2011), Chen et al. (2018) and Bianchi and Bigio (2020) and Gorton and Ordonez (2022)). We highlight how monetary policy that introduces liquidity in the system has nontrivial effects on the relationship between traditional banks and shadow banks, the composition of their portfolios, and the overall stability of the financial system.

On the theoretical front, we apply a network structure to understand how interlinkages (both at extensive and intensive margins) react to government interventions. Recent studies endogenize the effects of public interventions to the functioning of banking networks. Erol and Ordoñez (2017), for example, show that liquidity and capital requirements that are intended to provide stability may also dissipate a network structure that is useful in providing private insurance against financial shocks. More recently, Chang and Zhang (2021) study the role of regulations on the network structure, given balance sheets and Shu (2021) studies the impact

average stability at the cost of possible negative tail events. Normative implications would require explicitly introducing inefficiencies in the formation of banking networks and explicitly modeling the social cost of public liquidity provision. We leave these extensions for future research.

on balance sheets, given the network structure. Here, we combine in a single model both the endogenous choice of balance sheets and the networks structure, and provide evidence of those forces surrounding a large policy change.

In terms of financial network theory, Erol (2018) argues that uncapped ex-post liquidity provision induces a more centralized network by mitigating the insolvency contagion through core banks. Instead we show that ex-ante liquidity provision induces a less centralized network by reducing the value of liquidity coinsurance from core banks. In this sense, we also contribute to the literature of interbank networks and their effects on systemic risk, as in Allen et al. (2012) and Acemoglu et al. (2015). Empirically, Anderson et al. (2019) show how the concentration of interbank deposits affected systemic risk during the National Banking Era. This paper bridges these theoretical insights with empirical evidence.

The remainder of the paper is organized as follows: Section 2 provides historical background of the interbank system functioning before and after passage of the Federal Reserve Act. Section 3 discusses our novel historical dataset and presents empirical evidence of (i) an increase in banks' use of short-term borrowing, (ii) a reduction in the liquidity of nonmember banks (both cash and interbank deposits), and (iii) changes in the geographical structure of the core-periphery network. Section 4 studies a benchmark model of a correspondence relationship between two banks and portfolio choices, and then extends this benchmark gradually incorporating a central bank, more banks and a richer endogenous network structure. All proofs for this section are contained in Appendix C. Section 5 concludes.

2 Historical Background

During the National Banking Era (1864-1912), the U.S. banking system exhibited seasonal spikes in loan interest rates and frequent episodes of banking panics. Short-term interest rates displayed strong seasonal fluctuations due to large increases in the supply of deposits during agricultural harvest seasons and the demand for credit during agricultural planting seasons. As a result, banks faced liquidity pressures in spring and fall, and panics occurred at times of the year in which these pressures peaked.

The interbank system of this period, through the network of correspondent deposits and short-term funding, played an important role in relaxing these liquidity pressures. The reserve structure during the National Banking Era involved national and state banks and was described as an inverted pyramid: rural banks (country banks in agricultural regions) held their reserves in the form of correspondent balances (mostly, but not exclusively) in

banks in central reserve cities, especially New York City.⁶ The concentration of interbank deposits in New York City banks effectively transformed them into core banks to reallocate liquidity across regions. When rural banks faced seasonal demands, they withdrew their interbank deposits from financial centers, with those funds coming from other banks in areas where seasonal demands were less pressing. The geographical regional differences in demand produced somewhat offsetting flows of interbank deposits in New York City banks, which effectively provided private insurance across regions (Kemmerer (1910) and Carlson and Wheelock (2018a)). The interbank system helped banks meet seasonal liquidity pressures not only by allowing banks to cross-share deposits but also by allowing them to borrow short-term funds from correspondents. Country banks borrowed the most, reserve-city banks borrowed rarely, and central reserve-city banks borrowed hardly at all.

Although the interbank system helped soften the seasonal demands on banks in both its payment and funding facets, it did not create additional liquidity. As a result, the cash demands of country banks drained cash balances from New York City banks and led to seasonal spikes in interest rates. Contemporaries thought these seasonal swings contributed to bank panics and instability. This belief prompted calls for reform to create an *elastic currency* that would make the system less dependent on interbank relationships for seasonal liquidity (Sprague (1910)).

In response to this financial landscape, the Federal Reserve System was created in 1913 (under the Federal Reserve Act) with three primary objectives: to eliminate the concentration of bank reserves in New York City banks by establishing 12 regional reserve banks; to create an elastic currency and thereby reduce seasonal volatility; and to prevent panics (Calomiris (1994)). To achieve these goals, the Federal Reserve offered member banks access to public funds through discount windows in those 12 regional Federal Reserve Banks, requiring to hold reserves in vault cash or placing deposits in the Federal Reserve Bank instead of reserve-city and central reserve-city banks.⁷ Hence, to reduce the concentration of bank deposits in New

⁶The interbank system developed to overcome branching restrictions and facilitate interregional payments of goods and services. The National Banking Act institutionalized the interbank system by classifying banks in state banks and national banks and setting up a location-based three-tier system of national banks: central reserve-city banks (those located in New York City, Chicago, or St. Louis), reserve-city banks (banks in selected other large cities), and country banks (banks in all other locations). Central reserve-city banks were required to hold cash reserves equal to 25% of their deposits. Reserve-city banks were also required to hold reserves equal to 25% of their deposits, of which one-half could be deposits with a correspondent bank in a central reserve city. Country banks were required to hold reserves equal to 15% of their deposits, but they could keep three-fifths of the 15% as deposits with a correspondent bank in reserve and/or central reserve cities. State bank regulators subsequently passed similar laws.

⁷Even though only member banks were given access to Federal Reserve services, including the discount window, the Act made it possible to extend the discount window to nonmember banks in special circumstances with the approval of the Federal Reserve Board of Governors (see Carlson and Wheelock (2015)).

York City, interbank deposits could no longer be used to meet reserve requirements.⁸

The Federal Reserve Act made it compulsory for national banks to join, whereas it made it voluntary for state banks. Although the creators of the Federal Reserve System hoped to bring state banks under a more unified system of regulation and supervision, they failed to do so because most state banks chose not to join the system. By June 1915, only 17 state banks had chosen to join. In 1917, the Federal Reserve Act was amended to encourage state banks to participate. After the amendment, membership grew slowly, eventually reaching a peak of 1,648 state member banks in 1922 (compared with 19,141 state banks who remained nonmembers, according to Committee Branch Group (1935)).⁹ Even by 1929, only 5% of state banks in the U.S. had chosen to become members, with more than 60% of all banks remaining outside the realm of the Federal Reserve System.¹⁰

This lack of participation had two causes. First, the Act required members to hold reserves (in cash or with Federal Reserve), which did not pay interest. In contrast, state regulators allowed nonmembers to hold reserves in interbank deposits, which earned 2% interest (CQ Researcher (1923)). Second, member banks were subject to more stringent supervision and regulation than most nonmember banks.

The benefits of direct access to the Federal Reserve's discount window seem to have been insufficient to outweigh these costs of joining the system. The main reason is that nonmember banks were still able to gain access to public funds *indirectly* through their correspondent member banks. Before 1923, the Federal Reserve System was subordinated to the Treasury's goal of supporting World War I by issuing Liberty Bonds, so it allowed member banks to act as *agents* and rediscount for nonmember banks if government bonds were used as collateral (Federal Reserve Board (1917)).¹¹ In 1923, the privilege given to member banks to act as agents of nonmember banks was revoked in order to encourage state banks to join.¹² This restriction, however, had limited impact on the nonmember banks' ability to access

⁸The Federal Reserve Act retained for member banks the three-tier classification of central reserve city banks, reserve city banks, and country banks, but changed their reserve requirements. Member banks were required to hold 13%, 10% and 7%, respectively, of *demand deposits* and 3% of *time deposits* within the Federal Reserve Banks. These reserve requirements were first introduced in 1913, took effect in 1914 and were amended in 1917.

⁹In terms of relative size, member banks tended to be larger than nonmembers but nonmembers still held a sizable fraction of total deposits. In 1923, for instance, nonmember banks held more than a third of total U.S. commercial bank deposits (\$10.6 billion of a total of \$37.7 in the whole system).

¹⁰While there was some heterogeneity across states in terms of membership, in most states less than 4% of state banks joined the Federal Reserve System. The exceptions were northeastern states where membership among state banks topped 30%.

¹¹Between June 15th and July 15th of 1917, nonmember banks could access the discount window directly, just with the endorsement of a member bank if they used government bonds as collateral.

¹²After 1923, member banks were allowed to rediscount paper of nonmember banks as a temporary measure only during emergencies (Federal Reserve Board (1928)).

the discount window. When member banks could not rediscount the collateral received from their nonmember respondents, they would use their own eligible paper to borrow from the Fed and lend to their nonmember respondents against such collateral (CQ Researcher (1923)). Hence, nonmember banks continued to enjoy the benefit of having indirect access to the Fed’s discount window through the interbank system even after 1923 (Virginia State Banking Division (1928) and Gruchy (1937)).

3 Empirical Evidence

In this section, we introduce our novel dataset and explore how the creation of the Federal Reserve changed the role and structure of the interbank system for nonmember banks. These banks constituted the majority of banks, but they operated without access to public liquidity and outside federal regulation and supervision.

3.1 Data sources

We focus on the behavior of Virginia *state banks* that chose not to become members of the Federal Reserve System. In 1922, 323 out of 334 Virginia state banks were nonmember banks. State nonmember banks were regulated by state bank regulators. National and state member state banks were regulated by the Federal Reserve Bank of Richmond.

Our primary data comes from state bank examination reports for all state-chartered banks in Virginia. We collected reports for 1911 (before passage of the Act) and 1922 (after passage of the Act). State bank examination reports were introduced as part of regulators’ efforts to improve supervision of a banking system that expanded rapidly due to rising needs of industrialization and commercial activities.¹³ The Examination Reports provide a wealth of information regarding the ownership structure, corporate governance, and investment portfolios (Calomiris and Carlson (2014)). For the purposes of our analysis, the most valuable material is related to the relationships with correspondents.

We focus on the years 1911 and 1922 to avoid the transition period at the Fed’s foundational years. First, the Federal Reserve provided a three-year phase-in period allowing member banks to adjust to new reserve requirements after it started its operation in November 1914.

¹³In 1903, the Virginia banking law was amended to impose a more strict supervision of state banks. In 1910, the banking law was amended again to include provisions for the examinations of all state banks and other financial institutions. Bank examinations were first introduced in 1911. These reports were filled by regulators once or twice a year. Bank examinations were held annually in the 1910s, but were made semiannually in the 1920s (Gruchy (1937)).

Second, the Congress amended the 1913 legislation to increase state bank participation in 1917. Third, following the passage of the Federal Reserve Act in 1913, Virginia state bank regulators reduced reserve requirements for state banks in 1915. Fourth, the Federal Reserve began implementing expansionary monetary policy in 1917 to support the war effort during WWI, and short-term borrowing increased sharply for nonmember banks. Lastly, the Reserve Banks increased their discount rates sharply in 1920 and borrowing dropped sharply for both member and nonmember banks. In Online Appendices D and E, we use state bank balance sheets at the state and bank levels from 1910 to 1928 and show that balance sheet ratios displayed irregular patterns during these years, but returned to displaying regular patterns by 1922.¹⁴

Some regional reserve banks allowed nonmember banks to access the discount window in the early 1920s, but the Richmond Fed did not. The Richmond Fed was known to be a “conservative” district during the 1920s. It followed the real bills doctrine and took a strict stand on rediscounting, prohibiting nonmember banks to rediscount their commercial paper at the Fed directly (Wheelock (2004)). Still nonmembers were able to borrow short-term funds using “bills payable” (relatively worse collateral) through their correspondents in Virginia. In addition, they rediscounted their paper through correspondents in other Federal Reserve districts. (Virginia State Banking Division (1922)).

For a given bank, the dataset reports details of the balance sheet components and three types of interbank connections: deposits *due from* other banks, deposits *due to* other banks, and *borrowed money* from other banks, each with the dollar amount and the corresponding name and location of the correspondent. Examiners recorded detailed information on interbank deposits for regulatory purposes, as in Virginia nonmember banks could hold up to $\frac{7}{12}$ of required reserves in the form of interbank deposits with approved reserve agents.¹⁵

Examination reports also provide details on the use of collateral, the amount of the loan, and the identity of the lender. Banks could borrow a short-term loan from another bank while posting a loan or other security as collateral (“bills payable”) or by selling one of its loans to another bank (“rediscounts”).¹⁶ Examiners paid close attention to “borrowed money” because it was a good indicator of a bank’s credit position. Bills payable was the last resort for banks to increase funding after rediscounting all eligible commercial paper. An increase in the use

¹⁴Carlson and Wheelock (2018b) use national bank balance sheets aggregated at the state-level from 1894 and 1928 and also show that discount window lending and bank balance sheets displayed regular seasonal patterns until 1922.

¹⁵Virginia state bank regulators did not make differentiated reserve requirements for Richmond and country banks so we can analyze them jointly. Richmond was not a reserve city in 1911 but was one by 1922.

¹⁶Bills payable include certificates of deposits representing borrowed money, amounts due to other banks in the form of overdrafts, and notes and bills re-discounted with correspondent banks.

of borrowings from other banks using bills payable was taken by examiners as indication of an unhealthy financial position.¹⁷

While examination reports provide detailed information on payments and funding relationships, they raise concerns about spurious differences due to seasonal or other time-related factors given they were filed by examiners who visited each bank on different dates. We show the robustness of our findings in Section 3.4, using Call Reports. While they provide data with less detailed information on balance sheet categories, they provide information for all banks at the same point in time.

To gauge our new dataset, we report the average number of counterparties for the payments and funding relationships of all banks in Table 1. “Banks” indicates the number of banks in our sample, and “Respondents” those that either placed deposit and/or borrowed short-term funds. While all Virginia state nonmember banks placed interbank deposits (before and after the Fed), not all of them borrowed short-term funds. For instance, there were 200 state banks in 1911, all holding deposits in some other bank but only 59 banks borrowing short-term funds. Panel A shows all banks in our dataset and Panel B display those banks that operated in both years. In 1922 there were 146 *incumbent* banks that were already in operation in 1911, and 169 *new* banks that opened after the founding of the Fed.¹⁸

In the subsequent sections, we document changes in bank balance sheets and interbank relationships at the extensive (tracing which banks were part of a connection) and intensive (the dollar amounts of the deposits and loans that were involved in a connection) margins.

3.2 Changes in the Role of the Interbank System

Nonmember banks borrowed from member banks to access the discount window indirectly. In this section, we show Virginia state nonmember banks’ borrowing behavior and its effect on their balance sheets before and after the founding of the Fed. Table 2 presents information on the balance sheet composition of state/nonmember banks in Virginia for the years 1911 and 1922. In order to alleviate the concern that the balance sheet ratios are driven by new banks in 1922, we provide ratios for all banks in our sample and also for banks that were present both in 1911 and 1922. We highlight three empirical findings:

Finding 1: After the creation of the Federal Reserve, nonmember banks reduced the holdings of liquid assets (cash and deposits in other banks): First, the share of vault cash (specie and

¹⁷Borrowing had to be less than the bank’s capital and surplus. In addition, assets pledged as collateral had to be less than 150 percent of the amount borrowed (Virginia State Banking Division (1928)).

¹⁸Figure A2 in the Appendix maps respondent banks (Virginia state banks) and their correspondent banks for the years 1911 and 1922, only for banks that existed in both years.

Table 1: Payments and Funding Relationships, 1911 and 1922

	Banks	Respondents	Total Links	Mean	SD
Panel A: All Banks					
Year 1911					
Due-from	200	200	933	4.7	3.9
Borrowing	200	59	87	1.5	0.9
Year 1922					
Due-from	315	315	1025	3.3	2.3
Borrowing	315	160	252	1.6	0.9
Panel B: Banks both in 1911 and 1922					
Year 1911					
Due-from	146	146	635	4.3	3.4
Borrowing	146	37	55	1.5	0.8
Year 1922					
Due-from	146	146	581	4.0	2.6
Borrowing	146	82	133	1.6	0.9

Notes: “Due-from” indicates deposits in other banks. “Borrowing” indicates short-term borrowing from other banks. “Banks” indicate the total number of Virginia banks in the sample. “Respondent” indicates banks that either deposit or borrow. “Total links” indicate the total number of linkages of a respondent bank. *Source:* *Virginia State Bank Examination Reports*.

legal tender notes) significantly declined by roughly 33%, from 4.8% of total assets in 1911 to 3.2% in 1922. Second, the share of deposits in other banks also declined by roughly 30%, from around 13% of total assets to around 8%. The decline in liquid assets has a counterpart on an increase in illiquid asset holdings, such as bonds and loans.

Finding 2: After the creation of the Federal Reserve, nonmember banks increased the use of short-term borrowing: Short-term borrowing increased significantly, by almost 67%, from 3.3% of total liabilities in 1911 to 5.6% in 1922.

Finding 3: After the creation of the Federal Reserve, nonmember banks relied more on deposit financing and less on equity financing: Equity funding declined by about 5%, from 24% of total liabilities to 19% of total liabilities while demand deposit funding (mostly from households and firms) increased by about 3% of total liabilities.

These patterns suggest that the Fed changed the role of the interbank system, thereby reducing the aggregate liquidity of the banking system. On the liability side, banks borrowed more from their member correspondents. On the asset side, banks reduced interbank deposits. These changes indicate that banks relied more on short-term funds and less on interbank deposits to manage liquidity.

Table 2: Balance Sheet Ratios, Virginia State Banks, 1911 and 1922

	All Banks			Both in 1911 and 1922		
	1911	1922	Difference	1911	1922	Difference
Cash to assets	0.047 (0.029)	0.032 (0.028)	-0.016*** (0.003)	0.048 (0.030)	0.032 (0.034)	-0.016*** (0.004)
Duefroms to assets	0.126 (0.075)	0.089 (0.070)	-0.036*** (0.007)	0.129 (0.076)	0.077 (0.051)	-0.052*** (0.007)
Bonds to assets	0.038 (0.075)	0.066 (0.112)	0.029*** (0.009)	0.035 (0.075)	0.084 (0.116)	0.050*** (0.012)
Loans to assets	0.726 (0.125)	0.752 (0.147)	0.026** (0.013)	0.726 (0.131)	0.759 (0.141)	0.033** (0.016)
Equity to liabilities	0.252 (0.093)	0.219 (0.112)	-0.033*** (0.009)	0.242 (0.088)	0.191 (0.077)	-0.052*** (0.009)
Deposits to liabilities	0.693 (0.135)	0.707 (0.157)	0.014 (0.014)	0.704 (0.132)	0.736 (0.132)	0.033** (0.016)
Duetos to liabilities	0.016 (0.072)	0.011 (0.058)	-0.005 (0.005)	0.017 (0.083)	0.014 (0.070)	-0.004 (0.009)
Borrowing to liabilities	0.035 (0.059)	0.057 (0.076)	0.022*** (0.007)	0.034 (0.062)	0.056 (0.074)	0.022*** (0.008)
Obs.	200	315		146	146	

Source: *Virginia State Bank Examination Reports*.

3.3 Changes in the Structure of the Interbank System

In this section, we study how the founding of the Fed changed the structure of the interbank system by examining banks' individual relationships with their correspondents. While the founding of the Fed would have a direct impact on the network structure of member banks, it is unclear whether it would have an impact on the network structure of nonmember banks. This is because the Federal Reserve Act disallowed member banks to use interbank deposits to satisfy reserve requirements, but state regulators continued to allow state nonmember banks to do so.

Table 1 provides an initial insight into the change of the interbank network. First, banks reduced the number of *correspondent banks* (*depository counterparties*). The average number of correspondent relationships declined from 4.7 in 1911 to 3.3 in 1922. This reduction was

driven by entrants rather than incumbents. The number of correspondent relationships for incumbents remained largely unchanged, shown by a small decline from 4.3 to 4. Second, banks increased short-term borrowing; a third of all banks borrowed in 1911, but more than half did in 1922. This change was instead similar between entrants and incumbents.

We begin this analysis by presenting a specific example to illustrate our information about changes in a bank's relationships after the Federal Reserve creation. In Figure 1, we show the interbank relationships of the Bank of Warm Springs in Warm Spring, Virginia. The correspondent banks that received only deposits from the Bank of Warm Springs are in blue and the ones that both received deposits and lent short-term to the Bank of Warm Springs are in red. In the tabular component of the map, we also provide detailed information about these correspondent relationships. Columns (1) and (2) provide the names and locations of the correspondent banks. Columns (3) and (4) show the amount of interbank deposits due from these banks and the amount of short-term funds borrowed from them in each year.

Figure 1: Bank Network for Bank of Warm Springs

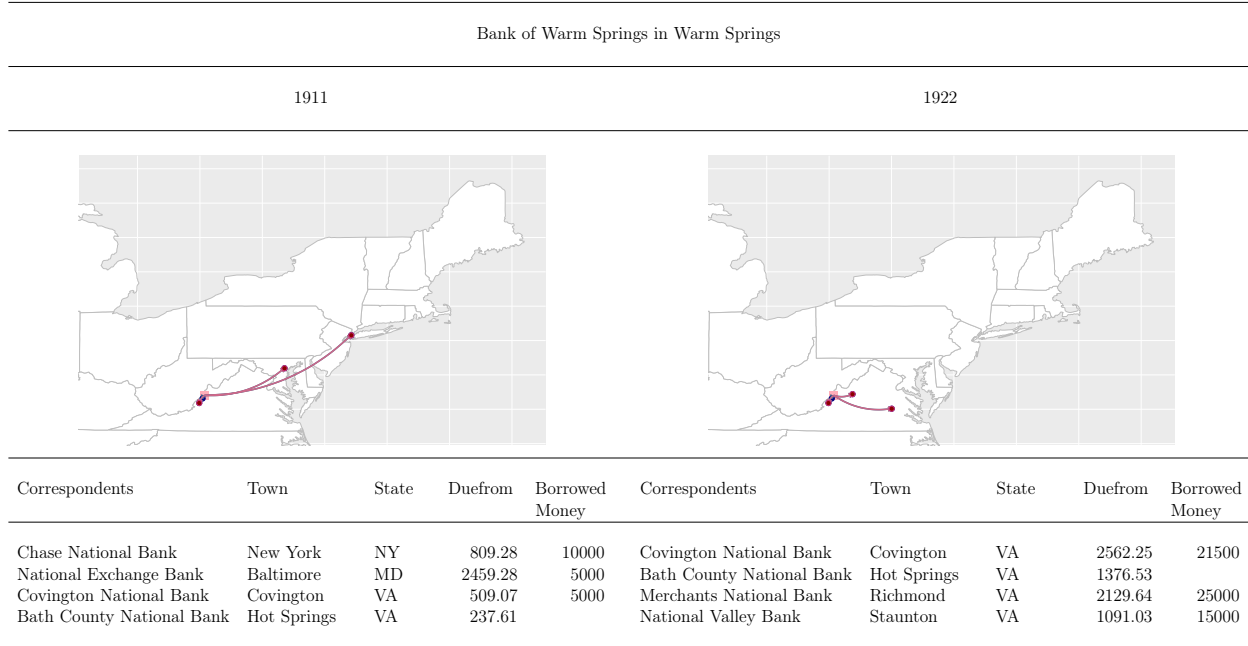


Figure 1 is an example of how the interbank system changed in two major ways after the introduction of the Fed. First, the funding role of the interbank system became more important than the payments role of the interbank system. While the volume of exposures to counterparties through interbank deposits increased modestly, the volume of exposure through interbank borrowing increased significantly. Second, correspondent relationships became more local. In 1911, Bank of Warm Springs maintained correspondent banking relationships in New York and Baltimore, but by 1922 it had dissolved these relationships

and opened new ones with banks in Richmond and Staunton, which were in close proximity. The changes made by Bank of Warm Springs are representative of the general patterns that characterize interbank networks before and after creation of the Federal Reserve System.

In Tables 3 and 4, we examine nonmember banks' exposures to their major counterparties. We examine the largest depository correspondent and the largest short-term funding provider separately because were not always the same. While banks held deposits in multiple correspondents, they typically borrowed from only one or two. The first two columns in each of these tables compare the exposure of existent banks between 1911 and 1922. The last two columns compare exposures between incumbents and new banks in 1922. We present two additional empirical findings:

Finding 4: After the creation of the Fed, nonmember banks became more exposed to the largest depository correspondent: From Table 3, we find that more existing banks became exposed to the largest depository correspondent by borrowing from them. While the size of exposures through interbank deposits (due from to total due froms) remain unchanged, the size of exposures through short-term borrowing increased. When we compare existing banks to new banks, we find that a fewer number of new banks borrowed. However, the size of exposures to the largest depository correspondent through both interbank deposits and borrowing was larger for new banks compared to existing banks.

Table 3: Exposures to the Largest Depository Correspondent

	Existing - Across Years			Across Banks		
	1911	1922	Difference	Existing	New	Difference
Due from to total due froms	0.663 (0.232)	0.651 (0.223)	-0.012 (0.026)	0.655 (0.217)	0.771 (0.216)	0.116*** (0.025)
Due from to total assets	0.084 (0.062)	0.049 (0.036)	-0.034*** (0.006)	0.048 (0.036)	0.077 (0.069)	0.028*** (0.007)
Borrowing to total borrowing	0.122 (0.302)	0.312 (0.396)	0.191*** (0.041)	0.315 (0.397)	0.318 (0.428)	0.004 (0.047)
Borrowing to total liabilities	0.012 (0.040)	0.030 (0.048)	0.018*** (0.005)	0.031 (0.048)	0.035 (0.056)	0.005 (0.006)
Respondent bank (deposits)	146	146		146	169	
Respondent bank (deposit & borrow)	24	66		66	67	
Correspondent bank (deposit)	65	56		56	75	
Correspondent bank (deposit & lending)	19	44		44	40	

Source: *Virginia State Bank Examination Reports*.

Finding 5: After the creation of the Fed, banks became more exposed to the largest short-term funding provider: From Table 4, we also find that more existing banks became exposed to

the largest short-term funding provider by borrowing from them. However, the size of exposures to the largest provider through interbank deposits and short-term borrowing remained unchanged for these borrowers. When we compare existing banks to new banks, the size of exposures to the largest short-term funding provider through both interbank deposits and borrowing was larger for new banks compared to existing banks.

Table 4: Exposures to the Largest Short-term Funding Provider

	Existing - Across Years			Across Banks		
	1911	1922	Difference	Existing	New	Difference
Due from to total due froms	0.515 (0.315)	0.537 (0.304)	0.022 (0.061)	0.527 (0.313)	0.715 (0.293)	0.188*** (0.048)
Due from to total assets	0.047 (0.046)	0.034 (0.035)	-0.012 (0.007)	0.034 (0.035)	0.051 (0.051)	0.017** (0.007)
Borrowing to total borrowing	0.770 (0.269)	0.755 (0.260)	-0.016 (0.052)	0.755 (0.260)	0.810 (0.246)	0.056 (0.04)
Borrowing to total liabilities	0.068 (0.063)	0.066 (0.049)	-0.002 (0.011)	0.066 (0.049)	0.085 (0.052)	0.020*** (0.008)
Respondent bank (total)	146	146		146	169	
Respondent bank (deposits & borrow)	37	82		82	77	
Correspondent bank (deposits & borrow)	27	46		46	45	

Source: *Virginia State Bank Examination Reports*.

In Tables 5 and 6, we document changes in the concentration of interbank relationships at the extensive (tracing which banks were part of a connection) and intensive (the dollar amounts of the deposits and loans that were involved in a connection) margins. As reported in Table 1, respondent banks had multiple correspondents with whom they placed deposits, but had usually only one correspondent from which they borrowed money. Hence, we examine payments and funding roles separately. We present three empirical findings on this front.

Finding 6: After the creation of the Fed, the payment network became less concentrated in financial centers with more deposits placed in local banks: Table 5 shows the distribution of nonmember banks' due-from deposits (payment network). After the Fed's founding, nonmember banks shifted their deposits away from New York and Baltimore and into other country banks in Virginia. Changes in the payment network were driven by 169 new banks rather than 146 incumbents, as shown in Table A1. In other words, the founding of the Fed reduced the need for banks to find correspondents in other regions to hedge against local liquidity shocks. These changes are consistent at both extensive and intensive margins.

Finding 7: After the creation of the Fed, the funding network became less concentrated in

Table 5: Geographic Payment Network, All Banks

Due from Deposits in:	Extensive Margin (Links)			Intensive Margin (Amount)		
	1911	1922	Difference	1911	1922	Difference
New York City	0.195 (0.184)	0.127 (0.167)	-0.068*** (0.016)	0.108 (0.163)	0.069 (0.140)	-0.038*** (0.014)
Baltimore	0.094 (0.180)	0.069 (0.166)	-0.025 (0.016)	0.110 (0.242)	0.070 (0.198)	-0.040** (0.020)
Washington, DC	0.022 (0.079)	0.017 (0.099)	-0.005 (0.008)	0.018 (0.075)	0.016 (0.108)	-0.002 (0.009)
Richmond	0.212 (0.200)	0.223 (0.277)	0.011 (0.022)	0.289 (0.326)	0.272 (0.346)	-0.017 (0.030)
Reserve Cities in Other States	0.024 (0.072)	0.034 (0.136)	0.010 (0.011)	0.026 (0.085)	0.040 (0.168)	0.015 (0.013)
Country Banks in VA	0.423 (0.279)	0.500 (0.345)	0.077** (0.029)	0.408 (0.368)	0.511 (0.406)	0.104*** (0.036)
Country Banks in Other States	0.027 (0.109)	0.028 (0.104)	0.001 (0.009)	0.031 (0.145)	0.017 (0.095)	-0.014 (0.011)
Obs.	200	315		200	315	

Source: *Virginia State Bank Examination Reports*.

financial centers with more local correspondents, but to a lesser extent than the payment network: Table 6 shows the structure of the short-term borrowing network (funding network). We find that the creation of the Fed reduced the concentration of short-term borrowing from correspondents in financial centers as well, but to a lesser extent than interbank deposits. Before the Fed's founding, 40% of country banks borrowed short-term funds from their correspondents in Richmond banks. After the Fed's founding, banks borrowed more heavily from other country banks in Virginia instead of from Richmond banks, reducing the amount of borrowing from Richmond banks by more than 20%. Much like the payments network, changes in the funding network were driven by 169 new banks rather than 146 incumbents, as shown in Table A2. These changes are consistent at both extensive and intensive margins.

Finding 8: After the creation of the Fed, the distance between respondents and correspondents for the payment network declined, but the distance between these banks for the funding network remained unchanged: We compute the distances in miles between respondent and correspondent banks. Table 7 shows the longest and average distance between each bank and its correspondent for both payments and funding relationships. The distance between

Table 6: Geographic Funding Network, All Banks

Short-term Borrowing from:	Extensive Margin (Links)			Intensive Margin (Amount)		
	1911	1922	Difference	1911	1922	Difference
New York City	0.083 (0.225)	0.088 (0.225)	0.005 (0.032)	0.075 (0.216)	0.085 (0.227)	0.011 (0.030)
Baltimore	0.128 (0.303)	0.074 (0.235)	-0.054 (0.036)	0.132 (0.312)	0.071 (0.234)	-0.062* (0.036)
Washington, DC	0.020 (0.122)	0.017 (0.118)	-0.003 (0.017)	0.019 (0.119)	0.016 (0.117)	-0.003 (0.016)
Richmond	0.363 (0.428)	0.213 (0.351)	-0.151*** (0.052)	0.367 (0.438)	0.211 (0.355)	- 0.156*** (0.052)
Reserve Cities in Other States	0.030 (0.137)	0.042 (0.177)	0.013 (0.023)	0.029 (0.137)	0.042 (0.175)	0.014 (0.022)
Country Banks in VA	0.341 (0.422)	0.536 (0.436)	0.195*** (0.060)	0.320 (0.419)	0.505 (0.446)	0.185*** (0.060)
Country Banks in Other States	0.034 (0.146)	0.031 (0.150)	-0.004 (0.021)	0.019 (0.116)	0.029 (0.147)	0.009 (0.019)
Obs.	59	160		59	160	

Source: *Virginia State Bank Examination Reports*.

correspondents and respondents for the payments network was greater than the funding network. After the Fed’s founding, this distance declined for the payment network, but remained unchanged for the funding network.¹⁹ This shift of correspondent relationships away from New York and toward local banks transformed a *national core-periphery structure* based in New York City into a *regional core-periphery structure* based in reserve cities.²⁰

The changes we have documented on the primary role of the interbank system may explain the changes on its structure. The payment network was more concentrated in New York than the funding network before the founding of the Fed because banks mainly managed liquidity through interbank deposits. As shown in Carlson and Wheelock (2018a), New York City

¹⁹These findings are consistent with Carlson and Wheelock (2018a) who document New York City banks provided private liquidity arrangement against regional liquidity shocks and smoothed interregional flows by pooling reserves from different regions (Gilbert (1983) and James and Weiman (2010)), and Jaremski and Wheelock (2020) who documented the concentration of correspondent linkages (at an extensive margin) at cities with regional Federal Reserve Banks.

²⁰This is also consistent with evidence from Odell and Weiman (1998) and Jaremski and Wheelock (2020) who present other evidence that after the founding of the Fed, banks increased their correspondent links to nearby cities with Federal Reserve offices.

Table 7: Distance between Respondent and Correspondent Banks, All Banks

	Due-froms			Short-term borrowing		
	1911	1922	Difference	1911	1922	Difference
Longest Distance	293.5 (151.2)	213.9 (422.6)	-79.7** (31.1)	144.0 (146.1)	162.9 (573.9)	19.0 (75.7)
Mean Distance	131.6 (74.0)	114.7 (405.1)	-16.9 (29.0)	101.4 (101.3)	130.4 (568.5)	29.0 (74.6)
Total Distance	638.2 (686.1)	366.9 (556.8)	-271.3*** (55.2)	247.1 (292.2)	219.8 (597.3)	-27.3 (81.2)
Obs.	200	315		59	160	

Notes: Distance is in miles

Source: *Virginia State Bank Examination Reports*.

banks provided private liquidity arrangement against regional liquidity shocks and smoothed interregional flows by pooling interbank deposits from different regions (*interregional insurance*). In contrast, banks tended to borrow locally when they could not withdraw interbank deposits (Redenius and Weiman (2011)). After the founding of the Fed, banks relied more on short-term borrowing and less on interbank deposits to manage liquidity. Since banks could borrow from other member banks close by, their borrowing became local. In addition, banks did not have to rely on interbank deposits in New York City banks to manage liquidity, so their payments relationships became more local as well.

To summarize, the creation of the Federal Reserve changed the role and structure of the interbank system for banks operating outside the Federal Reserve System in several dimensions. In the theoretical section, we construct a model that shows how the insurance role of an interbank system accommodates these findings and provides additional testable implications. Then, we use the model to obtain implications of how the creation of the Fed may have affected systemic risk in the banking system.

3.4 Robustness Checks using Alternative Datasets

We have studied changes in nonmember banks' portfolios and interbank connections for the years 1911 and 1922. One might be concerned that these changes may have been driven by other factors besides the creation of the Fed. In this section, we discuss some of these possible factors and address them using alternative datasets.

First, it might be that the change in the composition of banks' portfolios after the founding of the Fed originated from changes in regulatory requirements, not public liquidity provision. The Federal Reserve Act and Virginia state bank regulators did not change capital requirements or branching restrictions for members and state/nonmembers. However, both regulators reduced reserve requirements; the Federal Reserve Act and the Virginia state regulators reduced reserve requirements in 1917 and 1915, respectively. In Online Appendix E4, we use information from the Annual Report of the Comptroller of the Currency (OCC Reports) to exploit state-level differences in reserve requirements.²¹ We show that a reduction in liquidity cannot be explained by a reduction in reserve requirements, both for members and nonmembers.²² Further, even though changes in reserve requirements could have affected cash reserves and interbank deposits, it is less clear why it would have had an effect on short-term borrowing.

Second, one might be concerned that Virginia is not representative of the U.S. In Table 8, we use the OCC reports and document balance sheet ratios at the aggregate level. Here we focus on the periods 1910-1913 and 1922-1928 to avoid the early years of the Federal Reserve System when balance sheet ratios displayed irregular patterns as discussed in Section 3.1. We show that balance sheet ratios for state banks in the U.S. are consistent with bank balance sheet ratios for Virginia nonmember banks in Table 2.

Third, it might be that the changes in banks' balance sheets reflect the differences in the moment of the business cycle or seasonal cycles at which examination reports were conducted by Virginia regulators. To verify that our results are driven by these factors, we collect individual banks' call reports from the *Annual Report of the Banking Division of the State Corporation Commission* from 1910 to 1928. The banks were required to submit call reports to the Virginia State Banking Department on four particular days during the year. The state regulators published the balance sheets from the latest call in the Annual Report. In Table 9, we show the composition of banks' balance sheets for all banks in the sample and banks that were present before and after the Fed creation (again to alleviate the concern that the changes might have been driven by the expansion in the banking sector). In both cases, we find these results are consistent with those using examinations reports in Table 2. On the liability side, banks increased short-term borrowing. On the asset side, banks reduced liquid assets and investments.²³

²¹The *Annual Report of the Comptroller of the Currency* provides balance sheet data aggregated at the state level for national and state banks separately. We collect this data from 1910 to 1928. We focus on state banks and treat them as nonmember banks given that their Federal Reserve membership participation rate was low (on average, only 4% of state banks became members of the Fed by 1922).

²²This result is consistent with Carlson and Wheelock (2018b) and Carlson and Wheelock (2018a).

²³Starting in 1920, the call reports did not distinguish cash assets and interbank deposits separately on

Table 8: Balance Sheet Ratios, U.S. Aggregate, State Banks.

	1910-1913	1922-1928	Difference
Cash to assets	0.045 (0.018)	0.025 (0.016)	-0.020*** (0.002)
Duefroms to assets	0.140 (0.048)	0.083 (0.057)	-0.057*** (0.005)
Bonds to assets	0.113 (0.101)	0.178 (0.107)	0.066*** (0.009)
Loans to assets	0.628 (0.102)	0.611 (0.094)	-0.017** (0.009)
Equity to liabilities	0.207 (0.057)	0.138 (0.032)	-0.070*** (0.004)
Deposits to liabilities	0.709 (0.091)	0.783 (0.063)	0.073*** (0.007)
Duetos to liabilities	0.030 (0.022)	0.026 (0.022)	-0.005** (0.002)
Borrowing to liabilities	0.0231 (0.032)	0.0304 (0.028)	0.007*** (0.003)
Obs.	192	336	

Source: *Annual Report of the Comptroller of the Currency*.

To sum up, our analysis using examination reports provides new evidence that the presence of the Fed changed the role and structure of the interbank system. The ability of nonmember banks to borrow from member banks enabled them to reduce liquid assets, including interbank deposits. In addition, the ability of nonmember banks to borrow from member banks in local areas reduced the need for them to use interbank deposits in financial centers to manage liquidity, thereby making interbank relationships local. These finding on banks' portfolios are consistent both at the bank and aggregate levels with alternative datasets with an extended period of time.

4 Model

Motivated by the documented changes in the role and structure of the interbank system after the creation of the Federal Reserve System, we construct a model of endogenous network

the asset side of the balance sheet, so we cannot observe the behavior of interbank deposits after the founding of the Fed in Virginia state bank call reports.

Table 9: Balance Sheet Ratios, Virginia State Banks

	All Banks			Both periods		
	1910-1913	1922-1928	Difference	1910-1913	1922-1928	Difference
Liquid Assets to assets	0.196 (0.114)	0.126 (0.078)	-0.070*** (0.004)	0.200 (0.111)	0.121 (0.068)	-0.079*** (0.004)
Investments to assets	0.739 (0.131)	0.806 (0.106)	0.067*** (0.005)	0.741 (0.127)	0.828 (0.073)	0.087*** (0.005)
Equity to liabilities	0.248 (0.122)	0.204 (0.124)	-0.044*** (0.005)	0.232 (0.105)	0.172 (0.058)	-0.060*** 0.004
Deposits to liabilities	0.717 (0.139)	0.744 (0.174)	0.028*** (0.007)	0.740 (0.118)	0.789 (0.088)	0.049*** 0.005
Borrowing to liabilities	0.028 (0.051)	0.034 (0.060)	0.005** (0.002)	0.025 (0.046)	0.032 (0.051)	0.007*** 0.003
Obs.	968	2223		672	1140	
Number of Banks.	284	363		171	171	

Source: *Virginia State Bank Call Reports*.

formation and portfolio choices that accommodates these findings. We show that the major function of the interbank system is to provide banks *insurance through diversification* as shown by its properties before the creation of the Fed. This function becomes less important for banks after the founding of the Fed. Member banks could access the discount window directly, and nonmember banks could access it indirectly through their member correspondents. The theoretical predictions from the model are consistent with the changes in bank balance sheets and interbank relationships we observe in the data.

We begin with an environment with just two banks, a member and a nonmember, and analyze how the introduction of public liquidity affects their portfolios and interbank relationships. We then add more banks to study the structure of the interbank network. We start from an environment with no public liquidity. Then, we introduce public liquidity and show how the introduction of public liquidity affects bank portfolios and the interbank system.

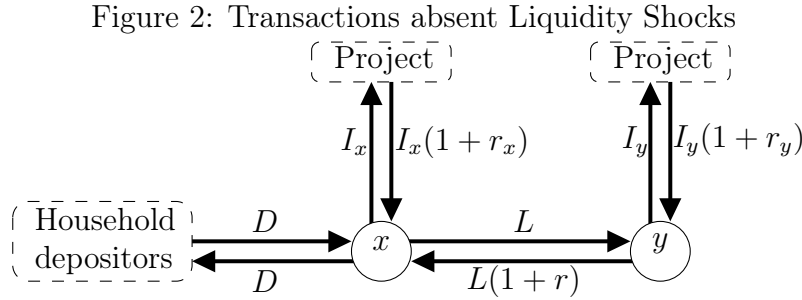
4.1 Environment

The economy is composed by two banks, x (nonmember bank) and y (member bank in a reserve city). Bank x accepts D household deposits and has access to a project that pays a net rate of return $r_x > 0$. Bank y does not receive household deposits and has access to a project that pays a net rate of return $r_y > 0$. Projects can be liquidated at any time

to recover the original investment, but projects can only be liquidated in full (*no partial liquidation*).

Reserves and investments After investments in the projects, some households may need their deposits, and withdraw from x before projects reach maturity, which we call a *liquidity shock*. As projects can only be liquidated in full, x wants to maintain reserves to cover withdrawals, and may do so in two ways, by holding cash or by depositing at bank y . We assume interbank deposit rates, r , are exogenous and lower than the projects' returns.²⁴

Denoting Φ_x the household deposits that x keeps as cash, and L the amount that x deposits at y , bank x invests $I_x = D - \Phi_x - L$. Assuming bank y is subject to reserve requirements in the form of holding a fraction ϕ of liabilities in cash, and denoting Φ_y the amount of interbank deposits that y keeps in cash, $\Phi_y \geq \phi L$. This implies that y invests $I_y = L - \Phi_y$. We call I_x and I_y *investments*, Φ_x and Φ_y *cash reserves*, and L the *interbank deposits*. Transactions and obligations as described, absent liquidity shocks, are shown in Figure 2.

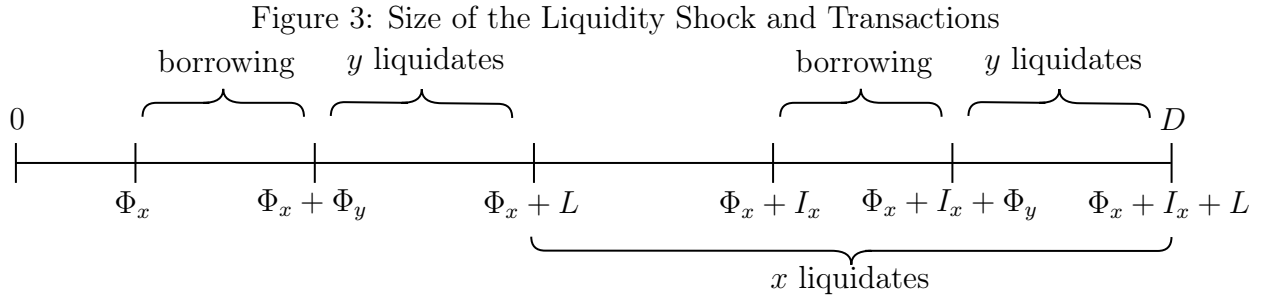


Liquidity shocks Liquidity shocks are caused by households withdrawing their deposits before projects mature. Deposit withdrawals can disrupt the previously depicted flow of funds. Our partial project liquidation assumption allows us to focus on liquidity crises and not solvency crises, as depositors can always recover D regardless of shocks, still maintaining the inefficiency of liquidations.

We denote early withdrawals by $\zeta \in [0, Z]$, where Z is the upper bound on possible withdrawals and ζ is drawn randomly from a distribution with CDF denoted by S . We call ζ the *liquidity shock*. Depending on the size of the liquidity shock and the size of investments, there are various scenarios that can materialize regarding project liquidations. In Figure 3

²⁴During the National Banking Era, state regulators allowed state banks to keep reserves at reserve cities to meet reserve requirements, and reserve city banks paid 2% (and no more than 2%) interest on those deposits, which justify our assumption that r is exogenous (See James (1978)). We further discuss the rationale for these assumptions in Online Appendix B

we show schematically all these scenarios for the situation in which, facing a withdrawal bank x always withdraws its deposits from y before liquidating the own project. Formally, this happens when $I_x + \Phi_y > L$ and $I_x r_x > Lr$, which are conditions on endogenous variables that we prove later (in Lemma 1) that always occur on the path of play.²⁵ The figure shows all possible withdrawals ζ , from nothing to all, and the borrowing and/or project liquidation outcomes those withdrawals would trigger. For instance, if withdrawals are such that $\Phi_x < \zeta \leq \Phi_x + \Phi_y$, x 's cash reserves are not enough and x borrows $\zeta - \Phi_x$ short-term from y to cover the withdrawals.²⁶ If for instance $\zeta > \Phi_x + L$, bank x would not have enough reserves to avoid liquidating its own project. The rest of regions can be similarly interpreted.



Based on these regions and the assumed probability distribution of withdrawals, we can compute ex-ante profits for both banks x and y . We define the probability that x 's project is not liquidated by

$$\Gamma \equiv S[\Phi_x + L]$$

and the probability that y 's project is not liquidated by

$$\Delta \equiv S[\Phi_x + \Phi_y] + (S[\Phi_x + \Phi_y + I_x] - S[\Phi_x + L])$$

In this setting bank y 's project always gets liquidated because of the liquidity shocks suffered by bank x . Then we can define the probability of *upstream contagion* simply by $1 - \Delta$.

Then, bank x 's and bank y 's expected profits are, respectively

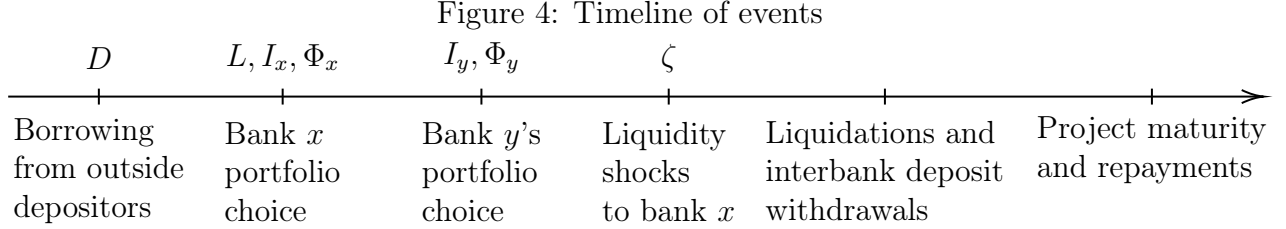
$$\Pi_x = \mathbb{E}[\pi_x] = \Gamma I_x r_x + \Delta Lr. \quad (1)$$

$$\Pi_y = \Delta (I_y r_y - Lr). \quad (2)$$

²⁵For expositional simplicity we focus on on-path scenarios, and we deal with off-path scenarios in the proof of Lemma 1.

²⁶Such lending is risk-free so we assume that y does not charge an interest. Given this, whether x borrows $\zeta - \Phi_x$ or Φ_y is inconsequential. In what follows, we assume that x borrows the smallest amount that suffices for it to ride out the shock, which is robust to the existence of small borrowing costs.

Timing Given the expected profits, bank x chooses investment I_x and deposits L , which determines its cash reserves Φ_x . Then y chooses investment I_y , which determines its cash reserves, which are subject to reserve requirements $\Phi_y \geq \phi L$.²⁷ Then, liquidity shocks materialize. This timeline is summarized in Figure 4.



4.2 Equilibrium without public liquidity

To obtain clean implications from closed-form solutions, we make the following assumption about the stochastic process defining liquidity shocks.

Assumption 1 (Liquidity Shocks). *With probability $\alpha \in [0, 1]$, ζ is drawn from $U[0, Z]$ with $Z \geq D$.²⁸ With probability $1 - \alpha$ there is no early withdrawal and $\zeta = 0$.*

Given this assumption, we can rewrite banks x and y 's expected profits from equations (1) and (2) as

$$\begin{aligned}\Pi_x &= \underbrace{\left(1 - \alpha \frac{I_x}{Z}\right)}_{\Gamma} I_x r_x + \underbrace{\left(1 - \alpha \frac{2L - 2\Phi_y}{Z}\right)}_{\Delta} Lr \\ \Pi_y &= \left(1 - \alpha \frac{2L - 2\Phi_y}{Z}\right) (L(r_y - r) - \Phi_y r_y).\end{aligned}$$

Expected short-term borrowing is

$$B = \mathbb{E}[b] = \frac{\alpha \Phi_y^2}{Z}.$$

We solve for subgame perfect Nash equilibrium, in which bank x chooses I_x and L to maximize Π_x subject to $I_x, L \geq 0$ and $I_x + L \leq D$, given that bank y chooses $I_y \in [0, (1 - \phi)L]$ to maximize Π_y .

²⁷Bank y always accept the deposit since its outside option is 0. We will assume that $(1 - \phi)r_y > r$ and so y strictly prefers to accept the deposit.

²⁸That a bank faces more withdrawals than deposits implies additional legacy liabilities by an amount $Z - D \geq 0$. This extension avoids kinks in the solution once we introduce public liquidity, but $Z > D$ is irrelevant in this part of the paper, and one can simply assume $Z = D$ for now. See Online Appendix B for a detailed discussion.

The next Lemma characterizes the choices of bank y . In particular it provides conditions under which bank y will choose to hold cash just to fulfill the reserve requirements.

Lemma 1. *Bank y 's binding reserve requirements.*

When interbank deposit rates are not too high (formally, $2r < (1 - \phi)r_x$ and $r < (1 - \phi)r_y$, where $\phi < 0.5$) and the probability of shocks is not too large (formally, $\alpha \leq \bar{\alpha} = \frac{Z}{Z + \rho D}$, with $\rho = \max \left\{ 0, \frac{2}{2 - \phi} \left(2(1 - \phi) - \frac{r}{r_y} \right) - 1 \right\}$), reserve requirements bind on the path of play: $\Phi_y = \phi L$. Moreover, $I_x + \Phi_y > L$ and $I_x r_x \geq Lr$.

Intuitively, when bank y 's project has a relatively high return (compared to the interbank deposit rate) and a relatively low probability of being liquidated by upstream contagion (when the probability of withdrawals bank x faces is not too large), bank y has incentives to invest in its project as much as possible, holding just enough cash to fulfill reserve requirements. In what follows, to focus on the decision of the nonmember bank x , we assume these conditions hold. Appendix B contains more discussion about these parametric conditions.

The next proposition shows how bank x 's balance sheet composition depends on the probability α that bank x suffers any withdrawal.

Proposition 1. *Equilibrium Portfolios Without Public Liquidity Provision.*

If $\bar{\alpha} \geq \alpha \geq \alpha_2$, bank x 's portfolio asset composition is

$$L = \frac{D + Z_\alpha}{4(1 - \phi)}, \quad I_x = \frac{D + Z_\alpha}{2}, \quad \Phi_x = D - I_x - L, \quad \Phi_y = \phi L.$$

where $Z_\alpha \equiv \frac{Z(1 - \alpha)}{\alpha}$ and $\alpha_2 \equiv \left(1 + \frac{D}{Z} \frac{1 - 2\phi}{3 - 2\phi} \right)^{-1}$.

If $\alpha_2 > \alpha > \alpha_1$, bank x 's portfolio asset composition is instead

$$L = \frac{D(r_x + r) - Z_\alpha(r_x - r)}{2(r_x + 2(1 - \phi)r)}, \quad I_x = D - L, \quad \Phi_x = 0, \quad \Phi_y = \phi L.$$

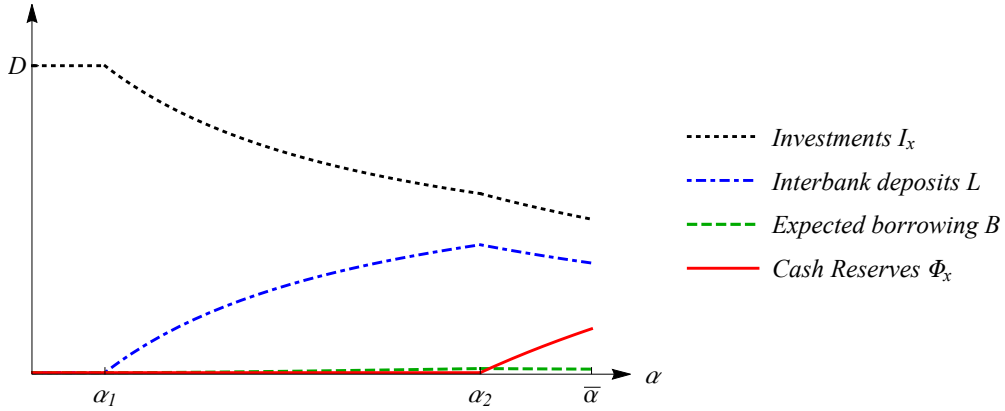
where $\alpha_1 \equiv \left(1 + \frac{D}{Z} \frac{r_x + r}{r_x - r} \right)^{-1} < \alpha_2$.

Finally, if $\alpha_1 > \alpha$, bank x does not hold cash or interbank deposits, and $I_x = D$.

Figure 5 illustrates Proposition 1. It shows the different components of bank x 's assets as a function of the probability α of any withdrawal, that follow a clear pecking order on investments. When the risk of withdrawals is very low ($\alpha < \alpha_1$), the return of an additional unit of investment for bank x is larger than the risk of liquidating the whole project, and

then x would rather invest fully in the project, without holding any cash or depositing in y . Once the risk of withdrawals increase enough ($\alpha_1 < \alpha < \alpha_2$), bank x reduces investment in the own project and places some deposits in y . The reason is intuitive: by depositing in y bank x *diversifies its portfolio* such that, in case of withdrawals that are not too large there is no need to liquidate a single large project but instead a smaller one (either x 's or y 's). Thus, as banks cannot liquidate a fraction of projects, diversification works through investing in smaller ones. Finally, once the probability of withdrawals is large enough ($\alpha_2 < \alpha < \bar{\alpha}$), bank x also holds some cash (the investment alternative with the lowest return).

Figure 5: Investments, Interbank Deposits, Short-Term Borrowing, and Cash Reserves



We also include in Figure 5 bank x 's expected borrowing from bank y . Naturally, as α increases, and bank x increases interbank deposits, bank y holds more cash in reserves which can be lent short-term to bank x in case of withdrawals, increasing bank x 's expected borrowing of bank y 's reserves.

This parsimonious setting provides a role for the connection between bank x and bank y ; deposits at bank y provide bank x diversification for bank x to face withdrawal shocks in the presence of no partial liquidations. This simple mechanism explains the composition of assets observed in our data. It also explains the extent of short-term borrowing that bank x may have as a function of expected withdrawals. In what follows we introduce public liquidity and study how these components change.

4.3 Equilibrium with public liquidity

Here we suppose there is a *central bank* that provides short-term liquidity only to y (hence a member bank), for a maximum amount m , which we refer to as *public liquidity provision*

($m = 0$ is the baseline case of no liquidity provision of the previous section). We assume bank x is not able to access m directly (hence a nonmember bank), but it can still access public liquidity indirectly through its interbank connection with y . We are interested in how the ability of x to indirectly access the central bank's liquidity affects x 's balance sheet and the relation with bank y .

This extension reflects the Fed's operation at the time. First, we assume there is a maximum available amount m of public liquidity, motivated by the fact that the Fed operated under the gold standard when it was created. When studying the effects on the system's fragility in the next section we will relax the deterministic nature of m , allowing for shocks to the supply of gold. Our results hold when m in optimal bank portfolios is replaced with the expectation of m . We also ignore the cost of borrowing from the Fed (possibly stigma for member banks) or the cost of borrowing from members (due to the quality of collateral for nonmember banks). Omitting these borrowing costs (directly or indirectly) is irrelevant to our qualitative insights.

Given that bank y can access up to m at no cost and that bank x can access m by borrowing from y at no cost, any shock ζ below m can be met at no cost just by borrowing short-term loans from the member bank. In contrast, a shock above m will require banks to use their own reserves or to liquidate projects, exactly as described in the previous section.

Formally, from the viewpoint of bank x , future shocks become $\zeta' = \max\{0, \zeta - m\}$, with ζ' equal to 0 with probability $1 - \alpha + \alpha \frac{m}{Z}$, and drawn from $U[0, Z - m]$ with probability $\alpha \frac{Z - m}{Z}$. We focus on the values of $m < Z$ so that public liquidity does not eliminate liquidity risk in the financial sector when liquidity shocks are large. We can rewrite bank x 's ex-ante profits, given m , as

$$\Pi_{x,m} = \underbrace{\left(1 - \alpha \frac{I_x - m}{Z}\right) I_x r_x}_{\Gamma_m} + \underbrace{\left(1 - \alpha \frac{2L - 2\Phi_y - m}{Z}\right) Lr}_{\Delta_m}. \quad (3)$$

The following proposition extends Proposition 1 with public liquidity provision.

Proposition 2. *Equilibrium Portfolios With Public Liquidity Provision.*

If $\bar{\alpha} \geq \alpha \geq \hat{\alpha}_2$, bank x 's portfolio asset composition is

$$L = \frac{D + Z_\alpha + m}{4(1 - \phi)}, \quad I_x = \frac{D + Z_\alpha + m}{2}, \quad \Phi_x = D - I_x - L, \quad \Phi_y = \phi L.$$

where $Z_\alpha \equiv \frac{Z(1-\alpha)}{\alpha}$ and $\hat{\alpha}_2 \equiv \left(1 + \frac{D}{Z} \frac{1-2\phi}{3-2\phi} - \frac{m}{Z}\right)^{-1}$.

If $\hat{\alpha}_2 > \alpha > \hat{\alpha}_1$, bank x 's portfolio asset composition is

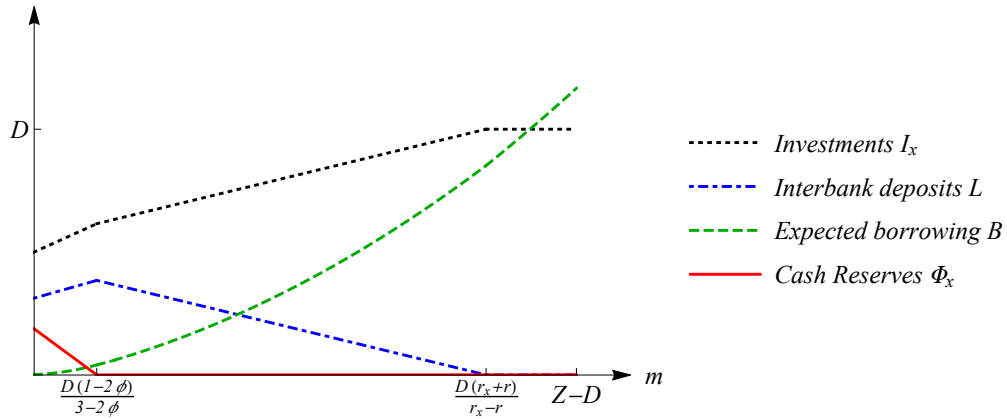
$$L = \frac{D(r_x + r) - (Z_\alpha + m)(r_x - r)}{2(r_x + 2(1 - \phi)r)}, \quad I_x = D - L, \quad \Phi_x = 0, \quad \Phi_y = \phi L.$$

where $\hat{\alpha}_1 \equiv \left(1 + \frac{D}{Z} \frac{r_x + r}{r_x - r} - \frac{m}{Z}\right)^{-1} < \hat{\alpha}_2$.

Finally, if $\hat{\alpha}_1 > \alpha$, bank x does not deposit or hold cash, and $I_x = D$.

Figure 6 shows how bank x 's choices change with public liquidity m for a level of α that, in absence of public liquidity, justifies x holding cash (this is $\bar{\alpha}$ in Figure 5). For low levels of m (first parametric case in the previous proposition), bank x chooses to hold less cash and increase both I_x and L as m increases. When m becomes large enough (second parametric case), x does not keep any cash, starts depleting their interbank deposits, and increases investments, I_x . All in all, the combined reserves of bank x , $\Phi_x + L$, decrease in m . Intuitively, indirect access to public liquidity reduces the need for holding reserves privately and diversifying one's portfolio, consistent with Finding 1. Even though this is not a calibration, a relatively small m seems consistent with the magnitude of changes in liquid assets and borrowing that we have documented in Finding 1.

Figure 6: Investments, Interbank Deposits, Short-Term Borrowing, and Cash Reserves



Equilibrium allocation as a function of central bank liquidity m in line with Propositions 2 and 3.

Notice that the behavior of bank x 's asset composition in response to increases in m is isomorphic to the behavior of bank x 's asset composition in response to reductions in α . In other words, more public liquidity effectively reduces the risk from liquidity shocks. In contrast, short-term borrowing increases both on m and α , resulting from the availability of public and private liquidity. We formalize these properties of short-term borrowing in the next Proposition.

Proposition 3. *Short-Term Borrowing with Public Liquidity Provision*

Expected short term borrowing is

$$B = \frac{\alpha}{2Z} (2(m + \Phi_y)^2 + m^2 - \max\{0, m + \Phi_y - L\}^2 - \max\{0, m + L - I_x\}^2)$$

which is strictly increasing in m in equilibrium.

Intuitively, bank x relies more on public liquidity provided through bank y as m increases. It is because there is more liquidity available to prevent liquidations and this allows bank x to hold more illiquid assets and a less diversified portfolio. This is consistent with Finding 2.

Remark on endogenous liabilities: We assume that bank x obtains funds exogenously from households and does not raise any equity. Endogenizing D implies that bank x internalizes the risk of early withdrawals on investments and requires a more complex structure to determine bank x 's debt/equity ratio. Regardless of the specific setting, bank x is less likely to raise household deposits when it faces a high level of withdrawal risk (high α). Bank x has more incentives to raise deposits when m increases since it reduces liquidity risk stemming from deposit withdrawals. These patterns are consistent with Finding 3.

Remark on adding possible counterparties: The investment decisions of bank x in response to an increase in α can be easily extended to the choice of depository institutions $y_1, y_2, \dots, y_N$ with individual project returns $r_{y1} > r_{y2} > \dots > r_{yN}$. When α increases, bank x starts to place more deposits in bank y and then moves to the next best opportunity, cash. With many possible counterparties, bank x would place deposits in the next best bank, y_2 , and then in y_3 , etc. An increase in m would revert the pecking order. Then, bank x would remove counterparties and mainly interact with their major counterparty, y_1 , to place deposits and borrow short-term funds. This result is a direct implication of public liquidity reducing the needs for diversification and would be consistent with Findings 4 and 5.

This first exercise with two banks highlights how the introduction of public liquidity changes the role of interbank relationships for nonmember banks. Even though they cannot obtain liquidity from the central bank, nonmember banks are less likely to diversify their portfolios and investments because they obtain it indirectly. Next, we extend this analysis by including additional counterparties to study the structure of the interbank network and how the introduction of public liquidity changes the structure of the interbank network.

4.4 Networks

In this section, we extend our framework to study how the structure of the interbank network changes in response to the provision of public liquidity. We show that banks move their interbank relations towards counterparts that are less costly to maintain. If it is less costly to maintain relationships with correspondents close in geographic proximity, banks choose to connect less to central reserve cities and more to regional reserve cities. Hence, public insurance crowds out the private insurance that smooths out cross-regional liquidity shocks.

We extend our analysis to four banks in two pairs. More specifically, banks x_1 and y_1 are linked as described in the baseline model, and the same is true for banks x_2 and y_2 . As before, banks x_1 and x_2 have household deposits and projects while banks y_1 and y_2 have interbank deposits received from x_1 and x_2 , and projects. We call $\{x_1, x_2\}$ *the periphery* and $\{y_1, y_2\}$ *the core*. Based on this general setting we proceed in two steps. First, in Section 4.4.1 we study how, in the absence of public liquidity, core banks coinsure each other through forming a sort of clearinghouse, as large New York banks historically did before the Federal Reserve Act. Then, in Section 4.4.2, we allow periphery banks located in different regions to choose their correspondents from among two groups of banks: those that have greater coinsurance possibilities but may be farther away (say, banks in New York) and those that have fewer coinsurance possibilities but may be closer (say, banks located in regional reserve cities). This allows us to study the effect of the central bank's liquidity provision m on the network structure. We show that central bank liquidity induces a shift of links from the far core (New York City) to the close core (regional reserve cities), thereby crowding out the private insurance that the system is able to provide. The creation of the Federal Reserve System produced a decentralized interbank network with more regional banking centers.

4.4.1 Liquidity coinsurance in the core

We assume that each of the core banks y_1 and y_2 has access to central bank liquidity, capped at (deterministic) m in total. We also assume that the shocks faced by x_1 and x_2 are negatively correlated, so we rule out competition over central bank liquidity. The next assumption is an extension of Assumption 1 to multiple banks x .

Assumption 2 (Liquidity Shocks for Two Banks). *With probability $\theta = \frac{\alpha}{2} \leq 0.5$ the shock ζ_1 is drawn from $U[0, Z]$ and the shock $\zeta_2 = 0$. With probability $1 - \theta$ the shock ζ_2 is drawn from $U[0, Z]$ and the shock $\zeta_1 = 0$. There is then a probability $1 - 2\theta = 1 - \alpha$ that there is no shock, and $\zeta_1 = \zeta_2 = 0$.*

This assumption guarantees that only one bank needs liquidity at a time and that we do not need to model the priorities of the central bank over which bank to provide liquidity to, and how much. In other words, we abstract from aggregate liquidity shocks in the system such that the central bank has to rescue both pairs of banks.

We further allow core banks y_1 and y_2 to insure each other against liquidity shocks coming from bank x by reallocating liquidity between the two. When x_i faces a liquidity shock, it can borrow from y_i , which can borrow from y_j as well as from the central bank.

With liquidity coinsurance at the core, the ex-ante profits of each bank x_i , given m , is

$$\Pi_{x_i} = \left(1 - \theta \frac{I_{x_i} - m - \phi L_j}{Z}\right) I_{x_i} r_x + \left(1 - \theta \frac{2(1 - \phi)L_i - m - \phi L_j}{Z}\right) L_i r$$

Notice this expression is the same expression as equation (3). The differences between the two are (1) it assumes that the conditions are under $\Phi_{y_i} = (1 - \phi)L_i$, (2) α is replaced by θ to adjust the probability for each bank x_i to suffer any withdrawal (from Assumption 2), and (3) it adds private liquidity from the core ϕL_j to the public liquidity m . This last piece is the most important. The core provides an additional source of liquidity to periphery banks in the case of early withdrawals. When early withdrawals occur, a periphery bank can borrow from its own core counterparty that can offer liquidity from three sources: its own reserves, the other core bank's reserves (since the other periphery bank does not need liquidity at the same time) and public liquidity provided by the central bank.

Public liquidity reduces interbank deposits in equilibrium for the same reason it reduces the need for banks to reduce diversification. Public liquidity encourages banks to hold less interbank deposits in core banks. This result is formalized in the next proposition.

Proposition 4. *Core Co-Insurance and Interbank Deposits*

If $m < D \frac{r_x + r}{r_x - r} - Z \frac{1 - \theta}{\theta}$. The equilibrium level of interbank deposits with and without liquidity co-insurance is given by

$$L_i^{no\ ins} = \frac{D(r_x + r) - (Z\theta + m)(r_x - r)}{2(r_x + 2(1 - \phi)r)} > L_i^{ins} = \frac{D(r_x + r) - (Z\theta + m)(r_x - r)}{2(r_x + 2(1 - \phi)r) + \phi(r_x - r)}$$

whereas $I_{x_i} = D - L_i$, $\Phi_{x_i} = 0$, and $\Phi_{y_i} = \phi L_i$ for both cases.

If $m > D \frac{r_x + r}{r_x - r} - Z \frac{1 - \theta}{\theta}$, $I_{x_i} = D$ for both cases.

This proposition shows that coinsurance from a counterparty at the core allows periphery banks to hedge against liquidity shocks and allows them to increase their own investments, at the risk of a large liquidation. Hence, banking network at the core acts as an additional

source of private liquidity on top of public liquidity provision, inducing more risk taking at the periphery. This result is in line with a well-known literature, at least from Jensen and Meckling (1976), that recognizes the role of insurance in inducing moral hazard, and of debt in inducing risk-taking. More recently, this is also consistent to Shu (2021) and Altinoglu and Stiglitz (2021), who study the role of interbank markets insurance provision on inducing excessive risk-taking. While these papers highlight the strategic complementarity of risk-taking in a network, our paper shows that insurance reduces the needs for diversification leading to too much concentration of risk within a single bank.

4.4.2 Endogenous network

Here we extend the framework to allow for banks to choose their counterparties, in particular their geographical location, and then study the implication of public liquidity provision for the network (re)shaping. Let x_i represent a bank in region i which can place deposits in a peripheral bank that is close (say a local reserve-city bank y_i^C) or a bank that is far but located in a financial core (say a New York City bank y_i^N). Similarly, let x_j represent a bank in region j , which can place deposits in a local reserve-city bank y_j^C or a New York City bank y_j^N . The assumption is that placing deposits in New York City banks implies higher costs because of the geographical distance (less information, higher danger and cost of moving funds, etc.) but access to the cross-insurance available within the core. As discussed above, two New York City banks y_i^N and y_j^N insure each other against liquidity shocks of their corresponding counterparties, reallocating liquidity within the system.

In the absence of the central bank x_i and x_j are more interested in connecting with a bank in the core to take advantage of the extra insurance. In the presence of public liquidity, however, they will rely less on insurance provided by the core, borrowing instead from local member bank y_i^C and y_j^C . There are, then, two options for equilibria. Banks can either connect to New York City banks for private insurance but pay higher costs, or they can connect to regional reserve city banks instead.

From the analysis in Section 4.4.1, if both banks connect to their regional correspondents,

$$\Pi_{x_i}^C = \left(1 - \theta \frac{(D - L_C) - m}{D}\right) (D - L_C) r_x + \left(1 - \theta \frac{2(1 - \phi) L_C - m}{D}\right) Lr$$

where L_C is given by $L^{no\ ins}$ in Proposition 4. If both banks connect to New York City banks,

$$\Pi_{x_i}^N = \left(1 - \theta \frac{D - L_N - \phi L_N - m}{D}\right) (D - L_N) r_x + \left(1 - \theta \frac{2(1 - \phi) L_N - \phi L_N - m}{D}\right) L_N r - c$$

where L_N is given by L^{ins} in Proposition 4.

The next Lemma shows that the relative gain to connect with core banks decline with the volume of public liquidity offered by the Federal Reserve System.

Lemma 2. *If $0 \leq m < D \frac{r_x+r}{r_x-r} - Z \frac{1-\theta}{\theta}$*

$$\frac{d(\Pi_{x_i}^C - \Pi_{x_i}^N)}{dm} > \frac{r(r_x - r)\phi}{2(r_x + 2(1 - \phi)r) + \phi(r_x - r)} \frac{\theta D}{Z} > 0.$$

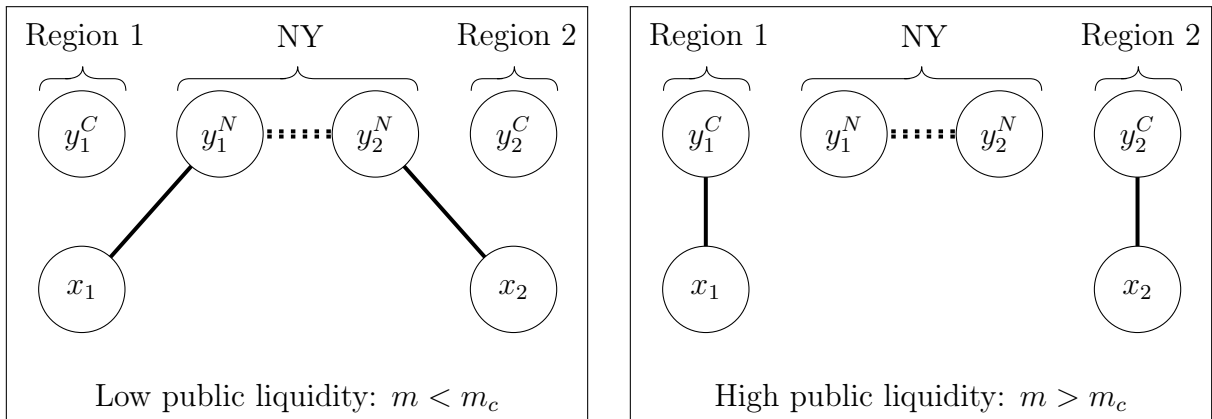
This characterization leads to the following proposition.

Proposition 5. *Network Geographic Concentration*

There exists m_c such that, for $m < m_c$, banks in both regions deposit their reserves at New York City banks, and for $m > m_c$ banks in both regions deposit their reserves in their corresponding reserve cities.²⁹

Under high enough public liquidity (when $m > m_c$), there are no deposits placed in New York City banks, as periphery banks do not need to rely on the cross-regional insurance from the core. Because public liquidity increases the ability of banks to absorb local liquidity shocks, x_i and x_j reduce their reliance on core banks and rely on local banks. A new network structure emerges as the concentration of links on the core decreases and the regions become more segmented. These changes are illustrated in Figure 7.

Figure 7: Network Reactions to Public Liquidity Provision



Change in the structure of the regional interbank network.

This result is consistent with Findings 6, 7, and 8. Those finding, however, were qualified by the *role of the link* (stronger for a payment network than a funding network) and the *age of*

²⁹We use stability as our equilibrium concept, which allows for x_1 and x_2 to deviate together.

the bank (stronger for banks created after the Fed’s founding). Next we discuss why these dimensions can easily be accommodated within our framework.

Role of Interbank Links: Payment network vs. funding network: Does public liquidity provision lead to a concentration of the *payment network* (i.e., interbank deposits relations) in the same extent as a concentration in the *funding network* (i.e., short-term borrowing relations)? The answer is generally no because the payment network is formed ex-ante (before withdrawal shocks arise) whereas the funding network is formed ex-post (after those shock arise). Hence, the payment network is “more strategic,” and the funding link is “more random.” This means that the previous analysis reflects the payment network better than the funding network. Two factors, however, created a positive correlation (even though imperfect) between payment and funding networks. One is mechanic: it was easier for banks to borrow from correspondents at which they hold deposits. The other is strategic: by threatening to withdraw the deposits from the correspondent, the later has more incentives to search for liquidity among its own counterparties, increasing the likelihood of the loan for the bank in need. Thus, even though the funding network has a larger random component, it is still correlated with the payment network.

Age of banks: New vs. incumbents: Does public liquidity provision affect the network of incumbents banks (created before the Fed) the same way as that of new banks (created after the Fed)? The answer is generally no because of the fixed costs of creating interbank relations. Since incumbent banks already chose their counterparties, they would be less inclined to change them even though public liquidity is introduced and they do not need to rely on correspondents for liquidity. In contrast, new banks would choose correspondents differently from existing banks because public liquidity is already provided. The fixed cost of creating counterparties makes new banks more reactive according to our theory, exactly as documented in our findings.

4.5 Testable implications

Our simple model can explain all changes we documented in the data after the creation of the Federal Reserve. The main mechanism works through replacing insurance through diversification with insurance via indirect access to public liquidity by borrowing from member banks. Public liquidity induced nonmembers to borrow more from members, hold less liquid assets, and invest more heavily in illiquid assets.

We can test this mechanism by comparing the portfolio structure of banks based on their borrowing status. We divide the 146 incumbent banks into four groups: (1) banks that did

not borrow at all, (2) banks that borrowed in both years, (3) banks that borrowed only in 1911, and (4) banks that borrowed only in 1922. In Table 10, we report balance sheet ratios for each group based on their borrowing status in 1922 and compute mean differences among groups using the Dunnett's method. On the asset side, banks that borrowed (either in both years or in 1922) held less liquid assets (cash and deposits) and increased lending. On the liability side, banks became less reliant on deposits and more dependent on short-term borrowing. This evidence shows that the banks that relied more on short-term borrowing also run a riskier business model, with less liquid assets and more loans.

Table 10: Balance Sheet Ratios by Borrowing Status, 1922

	none	1911 and 1922	1911 only	1922 only	Difference		
	(1)	(2)	(3)	(4)	(2) - (1)	(3) - (1)	(4) - (1)
Cash to assets	0.045 (0.055)	0.025 (0.014)	0.029 (0.012)	0.025 (0.011)	-0.019** (0.007)	-0.016 (0.010)	-0.020** (0.007)
Duefroms to assets	0.101 (0.053)	0.077 (0.049)	0.084 (0.048)	0.053 (0.039)	-0.024* (0.011)	-0.017 (0.014)	-0.048** (0.010)
Bonds to assets	0.122 (0.158)	0.051 (0.073)	0.082 (0.087)	0.073 (0.091)	-0.071** (0.026)	-0.039 (0.034)	-0.049* (0.023)
Loans to assets	0.695 (0.161)	0.806 (0.107)	0.760 (0.082)	0.787 (0.135)	0.110*** (0.030)	0.065 (0.040)	0.092*** (0.027)
Equity to liabilities	0.184 (0.064)	0.191 (0.107)	0.195 (0.072)	0.195 (0.068)	0.007 (0.017)	0.011 (0.023)	0.011 (0.016)
Deposits to liabilities	0.802 (0.065)	0.683 (0.156)	0.798 (0.0731)	0.692 (0.142)	-0.119*** (0.027)	-0.004 (0.036)	-0.111*** (0.024)
Duetos to liabilities	0.025 (0.108)	0.002 (0.004)	0.029 (0.102)	0.006 (0.017)	-0.023 (0.016)	0.005 (0.021)	-0.018 (0.014)
Borrowing to liabilities	0 (0)	0.110 (0.087)	0 (0)	0.088 (0.066)	0.110*** (0.013)	0.000 (0.017)	0.088*** (0.011)
Obs.	47	35	15	49			

To formally test whether the ability of banks to borrow changed banks' portfolios after the introduction of the Federal Reserve, we implement a difference-in-differences strategy. Motivated by the previous table, we define the introduction of the Federal Reserve System as the treatment event. The treated groups are three groups of banks that used short-term funds: *always a borrower* (those that borrowed in 1911 and 1922), *old borrower* (those that borrowed only in 1911), and *new borrower* (those that borrowed only in 1922). The control group is *never a borrower* (those banks that did not borrow in either one of the two years). Letting i denote one of the 146 banks that were present both in 1911 and 1922, and

$t \in \{1911, 1922\}$, our specification is:

$$Y_{i,t} = \alpha + \beta_1 * \mathbb{I}_j + \beta_2 * \mathbb{I}_j * \mathbb{I}_{1922} + \varepsilon_{i,t} \quad (4)$$

where $Y_{i,t}$ is the balance sheet ratios (such as the ration of cash to assets, or the ratio of equity to liabilities), $\mathbb{I}_j$ is an indicator function that takes the value 1 if bank i corresponds to group $j \in \{\text{always a borrower, never a borrower, old borrower, new borrower}\}$, and 0 otherwise, and $\mathbb{I}_{1922}$ is an indicator function that takes the value 1 if the year is 1922 (after the Fed's founding). The variable $\varepsilon_{i,t}$ is a mean-zero and possibly heteroskedastic error term. We cluster error terms at the bank level in order to account for the serial correlation of error terms. The coefficient β_2 captures the effect of the Fed's founding for the banks that borrowed and the banks that did not. We examine the effects of the Fed's founding on both asset and liability sides of balance sheets.

Table 11 presents the results for asset ratios. It shows that the creation of the Fed reduced the liquidity of the banks that borrowed. These banks reduced both cash and interbank deposits. A reduction in liquid assets is offset by an increase in loans. These changes are most pronounced in banks that borrowed in 1922.

Table 11: The Effect of the Fed's Founding on Bank Assets

	Cash to assets	Duefrom to assets	Bonds to assets	Loans to assets
<i>Always a borrower</i> x $\mathbb{I}_{1922}$	-0.029*** (0.005)	-0.051*** (0.014)	0.010 (0.018)	0.089*** (0.027)
<i>New borrower</i> x $\mathbb{I}_{1922}$	-0.030*** (0.005)	-0.075*** (0.012)	0.032* (0.019)	0.070** (0.027)
<i>Old borrower</i> x $\mathbb{I}_{1922}$	-0.026*** (0.006)	-0.044*** (0.016)	0.042 (0.026)	0.043 (0.028)
Observations	292	292	292	292
R2	0.12	0.29	0.11	0.10

Table 12 presents the results for liability ratios. The creation of the Fed did not have an effect on the banks that borrowed in both years, but it changed the liability structure of new borrowers. These banks changed their funding structure significantly. They reduced deposit financing, but increased equity financing and wholesale funding. While not explored in the model, banks liability structures would have affected a run risk. When banks reduce their dependence on household deposits and increase their reliance on short-term borrowing, they become less exposed to withdrawals by household depositors, but become more exposed to runs by institutional investors. This is because correspondent banks that provided short-term funding may not extend these short-term loans when they face liquidity shocks themselves.

To sum, these results suggest that the availability of short-term funding changed the funding structures of banks, altering also the nature of bank runs.

Table 12: The Effect of the Fed’s Founding on Bank Liabilities

	Equity to liab	Deposits to liab	Duetos to liab	Borrowing to liab
<i>Always a borrower</i> $\times \mathbb{I}_{1922}$	-0.008 (0.020)	-0.008 (0.025)	-0.028* (0.017)	0.017 (0.015)
<i>New borrower</i> $\times \mathbb{I}_{1922}$	0.036** (0.015)	-0.107*** (0.031)	-0.046* (0.026)	0.088*** (0.009)
<i>Old borrower</i> $\times \mathbb{I}_{1922}$	-0.017 (0.034)	0.146*** (0.035)	-0.007 (0.031)	-0.112*** (0.018)
Observations	292	292	292	292
R2	0.11	0.20	0.22	0.51

4.6 Implications for systemic risk: Fragility and vulnerability

We have constructed a parsimonious model that shows how banks adjusted their portfolios and interbank relationships in response to public liquidity provision by the Federal Reserve System and highlights how diversification provides insurance in interbank markets. In this section, we explore the implications for different categories of risk in the financial system.

It is informative first to clarify that, given the linearity and simplicity of our setting, it is easy to identify the unconstrained first best. The unconstrained optimum would be for each bank to invest in its own project fully, as this is the project with the highest return. In the presence of withdrawal shocks, this is not the optimal anymore as banks would diversify to minimize the likelihood and size of project liquidations. If public liquidity were costless, central banks providing an unlimited amount of public liquidity would be indeed desirable, as banks could meet withdrawals while investing all in the most productive project without the need to liquidate it.

To depart from such trivial benchmark and add fragility in the system, we need to allow for the possibility of liquidations on path. We assume that, although banks expect public provision of liquidity, they do not know the exact amount of such public liquidity. The uncertainty regarding the size of public liquidity is problematic for both member and nonmember banks, but this problem is more prominent for nonmember banks. Nonmembers are usually uncertain about the indirect access through members, changes in regulations, political considerations, implicit bailouts, etc. If banks overestimate the availability of public liquidity, they will hold too much in illiquid assets and may have to liquidate investments. We model this uncertainty with stochastic m , such that there may be a shock high enough to require

the liquidation of projects. Given the linearity of projects returns, all of our earlier analysis go through simply by replacing m with $\mathbb{E}[m]$ in the equilibrium quantities.

There are different ways to categorize risks in the financial system in this extended setting with uncertain public liquidity. A first category involves the identity of projects that need liquidation. *Direct risk* refers to the probability that the project of x gets liquidated as a consequence of the (direct) liquidity shock to x . *Contagion risk* refers to the probability that the project of y gets liquidated as a consequence of x withdrawing its interbank deposits from y . *Systemic risk* refers to the probability that all projects get liquidated.

A second category is based on banks' demand for public liquidity and their use of it. On the one hand *fragility* refers to the liquidation risk of portfolios, where these portfolios are chosen based on expected liquidity shocks and expected public liquidity. Fragility takes into account all sources of liquidity. A fragile economy, then, is an economy that is more likely to have less than expected public liquidity. On the other hand, *vulnerability* refers to the liquidation risk of portfolios if there were no public liquidity available ex-post, where these portfolios are chosen based on expected liquidity shocks and expected public liquidity. Vulnerability takes into account only private liquidity. A vulnerable economy, for instance, would be the one with very large projects and very few private reserves. A large provision of public liquidity would make an economy highly vulnerable but not fragile.

Introducing stochastic public liquidity can in principle complicate the analysis dramatically. To obtain closed-form results that clarify comparisons, we suppose that m is 0 with probability β and follows a uniform distribution with probability $1 - \beta$, such that m has mean m^* and mass β at no public liquidity $m = 0$. The next Proposition characterizes the effect of expected public liquidity m^* on the different categories of risk defined above,

Proposition 6. *Systemic Risk*

All notions of fragility are decreasing in m^ . Direct vulnerability increases in m^* . There is a threshold $\bar{m}$ such that systemic vulnerability and contagion vulnerability increases in m^* initially (when $m^* < \bar{m}$) and then decreases in m^* (when $m^* > \bar{m}$).*

The nonlinearity of contagion and systemic vulnerability in this proposition follows almost directly from nonmember banks' portfolios as a response of m^* , in Figure 6. When expected public liquidity, m^* , is relatively low, banks invest more on their own project and in interbank deposits as m^* raises, increasing direct and contagion vulnerability. Once m^* is large enough, banks keep investing more on their own project as m^* raises, but less on interbank deposits, increasing direct vulnerability but decreasing contagion. This implies that after a critical

threshold of public liquidity provision, most risk of liquidation gets concentrated among nonmember banks, with contagion to members being relatively less of a concern.

The opposite movement of fragility and vulnerability is also interesting. When there is no expectation that central banks will provide liquidity support (this is $m^* = 0$), fragility and vulnerability are the same. In that situation, projects that are vulnerable *because* they may be liquidated without public liquidity support will indeed be liquidated. The larger the expected injection of public liquidity, the lower is the fragility given a level of system vulnerability. The effect of expected public liquidity on fragility then has two components. An *injection effect* – more expected public liquidity always reduces the need for liquidation – and an *equilibrium effect* – more expected public liquidity reduces private liquidity and increases the need for liquidation. Notice that the equilibrium effect in the evaluation of fragility is, in fact, what we referred to as vulnerability.

$$\text{Fragility} = \text{Vulnerability} - \text{Injection Effect}$$

Intuitively, this explains why all measures of fragility decline given a level of vulnerability in Proposition 6 (all projects are less likely to be liquidated when there are large amounts of public liquidity in the system). Vulnerability, however, measures the exposure of the system to the need for liquidation.

Remark on the costs of systemic risk: The provision of public liquidity can be uncertain but also costly: distortionary taxation, inflationary costs, redistributive concerns, etc. When these costs exist, vulnerability translates into the cost of reducing fragility (as the injection becomes costly socially). If it is costly to provide public liquidity, the increase in vulnerability implies that the Fed will have to bailout a large size project when bank x suffers withdrawals, at a cost that is not internalized by bank x . In the absence of public liquidity, banks would respond by diversifying and investing in both projects x and y , which is also costly in terms of total output. The welfare implication of public liquidity provision depends on this comparison of these social costs.

5 Conclusion

Academics and policymakers have long questioned the role of interbank markets and how the provision of public liquidity affects it. Answering this question is difficult due to the complexity of modern banking, the ubiquitous presence of central banking, and the presence of intermediaries that participate outside their realm (the so called shadow banking). We have

examined this question by exploring how banks’ portfolios and connections change after the creation of the Federal Reserve System. We construct a unique historical data on individual payments and funding relationships of state/nonmember banks in Virginia and show that the introduction of the Federal Reserve System changed both the role and structure of the interbank system in non-trivial ways.

The role of the interbank system changed because nonmember banks borrowed from member banks indirectly to access public liquidity. Nonmembers became more dependent on short-term loans and less dependent on interbank deposits to manage liquidity, making a funding network more important than a payments network. This change makes the system more vulnerable to wholesale funding runs and financial contagion. Individual banks’ portfolios also changed in response, with less cash and interbank deposits and more illiquid assets. These changes also increased the overall vulnerability of the banking system. The structure of the interbank system also changed as interbank relationships became more concentrated at regional levels with less dependence on banks in financial centers, such as New York.

By constructing a parsimonious interbank model, we show that insurance across banks through diversification is the role of interbank markets that accommodate all these changes. We use the model to derive implications of public liquidity in terms of systemic risk. Even though the Federal Reserve System succeeded in stabilizing the interbank market upon its creation, it may have been building vulnerabilities in the banking system, as evidenced by the banking panics of the Great Depression.

These results open questions about the role of the Federal Reserve in creating a banking system prone to a large negative tail event, which may have been relevant for the magnitude of the Great Depression. It also has important implications for policy today. Financial regulations following the financial crisis of 2007-2009 attempt to prevent non-bank financial institutions from accessing public liquidity. As our results show, restricting “official” access to public liquidity does not prevent “effective” access to public liquidity, creating a landscape favorable to the flourishing of shadow banks that operate with illiquid assets and connect in ways that induce systemic risk.

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A Virginia State Bank Examination Reports

In Figure A1 we present images of representative pages in the state bank examination reports used for this study. The reports provide information on three types of interbank relationships: on the asset side of the balance sheet, the amounts due from other banks by individual debtor banks; on the liability side of the balance sheet, the amounts due to other banks by individual creditor banks; and the amounts of borrowed money and the provider of these short-term loans. In some cases, the reports provide information on collateral used for securing short-term funds.

Figure A1: Virginia State Bank Examination Reports

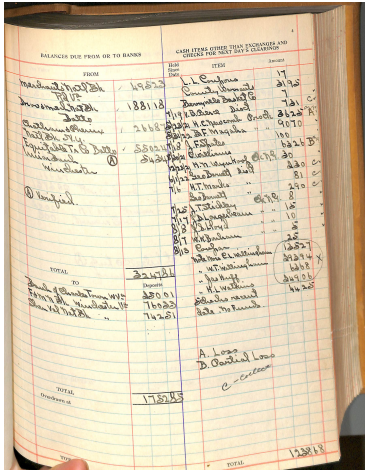
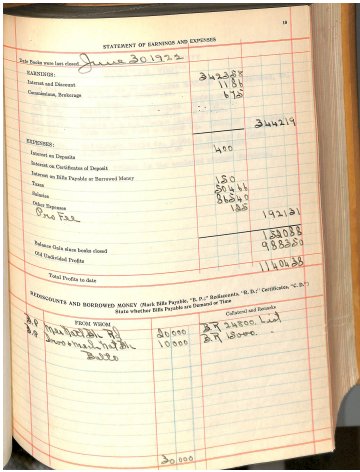
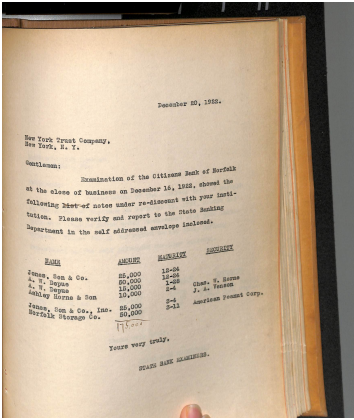
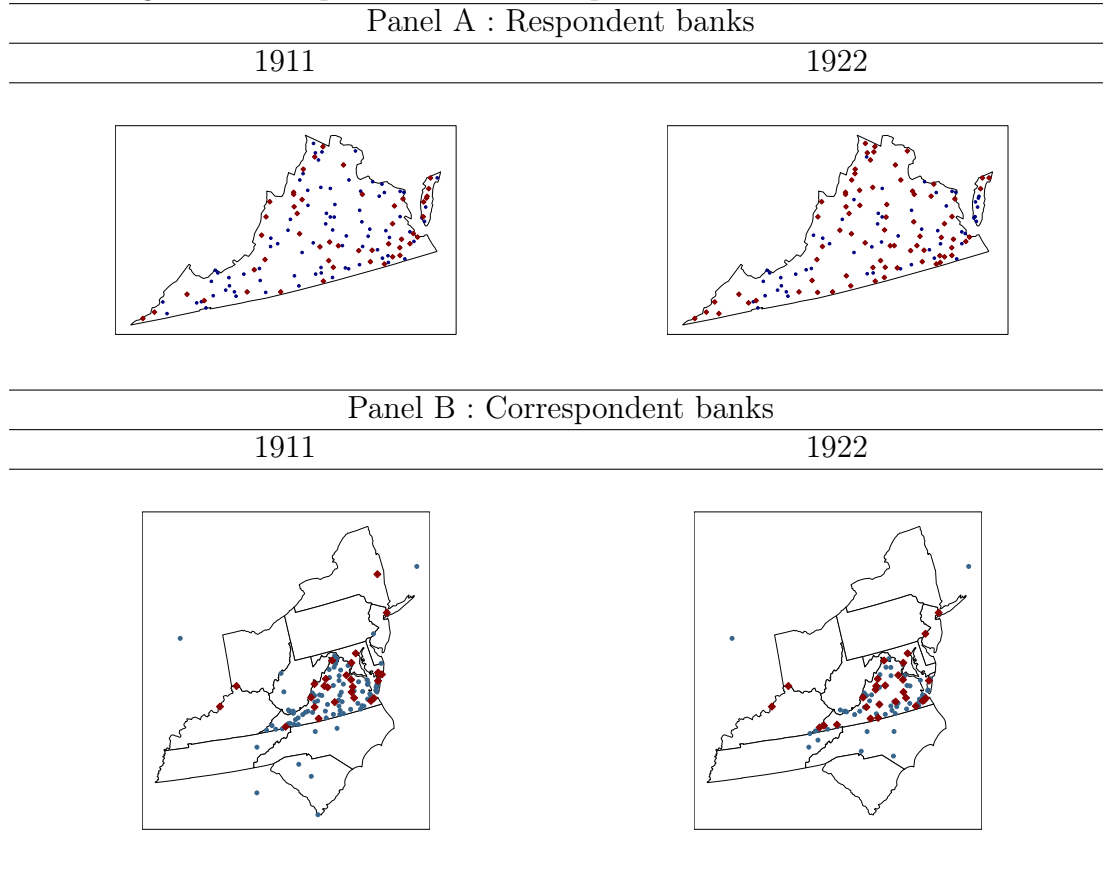
Interbank Deposits	Short-term Borrowing	Collateral for Borrowing
		

Figure A2: Respondent and Correspondent Banks, 1911 and 1922



Notes: Figure A2 maps all respondent banks (Virginia state banks) and correspondent banks for the years 1911 and 1922. The respondent (corresponding) banks that *only* placed (received) deposits are in blue, while banks that *both* placed (received) deposits and borrowed (lent) short-term funds are in red.

Source: *Virginia State Bank Examination Reports*.

Table A1: Distribution of “Due from” Deposits, Incumbents vs. New Entrants, 1922

	Extensive Margin (Links)			Intensive Margin (Amount)		
	(1)	(2)	(3)	(4)	(5)	(6)
	Existing Bank	New Bank	Difference	Existing Bank	New Bank	Difference
New York City	0.176 (0.171)	0.0848 (0.151)	0.091*** 0.018	0.0980 (0.151)	0.0451 (0.124)	0.053*** 0.016
Chicago	0.000360 (0.00436)	0 (0)	0.001 0.001	0.000111 (0.00134)	0 (0)	0 0
Baltimore	0.0966 (0.193)	0.0465 (0.135)	0.05*** 0.018	0.0957 (0.219)	0.0483 (0.176)	0.048** 0.022
Washington, DC	0.0135 (0.0611)	0.0210 (0.122)	-0.007 0.011	0.00597 (0.0472)	0.0243 (0.141)	-0.018 0.012
Richmond	0.234 (0.240)	0.213 (0.307)	0.021 0.032	0.325 (0.339)	0.226 (0.347)	0.1** 0.039
Reserve Cities in Other States	0.0279 (0.106)	0.0400 (0.158)	-0.012 0.016	0.0372 (0.151)	0.0431 (0.182)	-0.006 0.019
Country Banks in VA	0.426 (0.301)	0.564 (0.368)	-0.138*** 0.039	0.422 (0.372)	0.590 (0.420)	-0.168*** 0.045
Country Banks in Other States	0.0256 (0.0780)	0.0304 (0.122)	-0.005 0.012	0.00838 (0.0453)	0.0250 (0.122)	-0.017 0.011
Obs.	146	168		146	168	

Notes: Rows indicate the location of correspondent banks. New York was a central reserve city. Baltimore and Washington, DC, were reserve cities. Richmond was not a reserve city in 1911 but was one by 1922. Columns indicate the location of respondent banks. Extensive margins are the proportions of links in each location against total links. Intensive margins are proportions of correspondent deposits held at different locations against total due-from deposits. Standard deviations in parentheses.

Source: *Virginia State Bank Examination Reports*.

Table A2: Distribution of Borrowed Money, Incumbents vs. New Entrants, 1922

	Extensive Margin (Links)			Intensive Margin (Amount)		
	(1)	(2)	(3)	(4)	(5)	(6)
	Existing Bank	New Bank	Difference	Existing Bank	New Bank	Difference
New York City	0.140 (0.278)	0.0344 (0.135)	0.106*** 0.035	0.135 (0.280)	0.0358 (0.144)	0.1*** 0.034
Baltimore	0.0908 (0.258)	0.0566 (0.208)	0.034 0.036	0.0875 (0.260)	0.0539 (0.205)	0.034 0.036
Washington, DC	0.0181 (0.122)	0.0154 (0.114)	0.003 0.018	0.0137 (0.110)	0.0186 (0.125)	-0.005 0.018
Richmond	0.289 (0.387)	0.134 (0.292)	0.155*** 0.053	0.295 (0.396)	0.128 (0.289)	0.167*** 0.053
Reserve Cities in Other States	0.0251 (0.129)	0.0601 (0.215)	-0.035 0.028	0.0309 (0.150)	0.0537 (0.198)	-0.023 0.027
Country Banks in VA	0.415 (0.422)	0.660 (0.418)	-0.245*** 0.066	0.394 (0.425)	0.615 (0.442)	-0.221*** 0.067
Country Banks in Other States	0.0221 (0.127)	0.0391 (0.171)	-0.017 0.024	0.0235 (0.132)	0.0334 (0.162)	-0.01 0.022
Obs.	83	81		84	85	

Notes: Rows indicate the location of correspondent banks. Extensive margins provide information on the proportions of links in each location against total links. Intensive margins provide information on the proportions of borrowed money from correspondents at different locations against total borrowed money. Standard deviations in parentheses.

Source: *Virginia State Bank Examination Reports.*

B Remarks on the model and assumptions

The size of the liquidity shocks. We assume that the liquidity shock can exceed D so we do not deal with the corner solutions. In particular, the liquidity shock ζ is 0 w.p. $1 - \alpha$ and $U[0, Z]$ w.p. α where $Z > D$. The story is as follows. There are legacy assets and liabilities. M captures the sum of legacy liabilities and K captures the sum of returns from illiquid legacy assets. These are safe but the return time for legacy assets and withdrawal time for legacy liabilities are random. $K \geq M$ so there is no solvency issue. There can be an illiquidity issue. At the time of the liquidity shock, if the return so far from legacy assets is k and the amount of legacy liabilities realized so far is m , and the realized liquidity withdrawal from depositors (who have seniority) is $d \in [0, D]$ then the actual liquidity need at the time of the liquidity shock is $l = d + m - k$. We assume that l has distribution $U[-K, D + M]$. Now denote $\alpha = \frac{D+M}{D+M+K}$ and $Z = D + M$. Then $l \leq 0$ w.p. $1 - \alpha$ and $l \sim U[0, Z]$ w.p. α . Now let $\zeta = l_+$ the private liquidity need. (We use the notation $z_+ = \max\{z, 0\}$.) Then $\zeta = 0$ w.p. $1 - \alpha$ and $U[0, Z]$ w.p. α . When there is central bank liquidity m , the effect of m will be to make the private liquidity need $(\zeta - m)_+$.

Notation. Going forward, the fundamentals of the model are r_x, r_y, r for the return rates, α, Z, ζ , for shocks, D, m for liquidity. Denote $Z_{\alpha, m} = \frac{Z(1-\alpha)}{\alpha} + m$. For a random variable X , F_X denotes its CDF. Also, $f \underset{z}{\propto} g$ means that f and g are monotone transformations of each other as functions of z .

Discussion of parametric assumptions. We will take Z to be large enough compared to D and m in order to avoid corner issues in the algebra. In particular, $Z > m + D$ so that even the entire liquidity in the system may not suffice, although this event has small probability. This way, we do not need to worry about cumbersome corner solutions in the algebra. This, in a way, “convexifies” the problem.

Assumption 3. $0 \leq m \leq Z - D$.

Also, for technical reasons and for the simplicity of algebra, we will restrict attention to α that is not too large.

Assumption 4. $\alpha \leq \bar{\alpha} = \frac{Z}{Z + \rho D}$ where

$$\rho = \max \left\{ 0, \frac{2}{2 - \phi} \left(2(1 - \phi) - \frac{r}{r_y} \right) - 1 \right\}$$

The major role of this assumption is to make sure that the reserve requirements bind and $\Phi_y = \phi L$. Finally, we assume that r_x and r_y are relatively large compared to r .

Assumption 5. $(1 - \phi)r_x > 2r$ and $(1 - \phi)r_y > r$.

The condition on r_y is innocuous. If $(1 - \phi)r_y$ were less than r , y would not borrow. The condition on r_x deserves some discussion. One might think, at first, that by $r_x > r$, bank x 's own project is a better investment than the “interbank investment” of lending to y . Since each investments provide buffer against liquidation of the other, each investment would be non-zero under sufficiently high risk. But by $r_x > r$, I_x would be larger than L . But this simple logic is missing a critical point. Bank y pays interest on the full loan L , not the investment size I_y . At least ϕL is kept by y as reserves, which is a source of short term liquidity for x at the time of shocks. That is, interbank investment has an extra benefit above and beyond its investment value and diversification value. This complicates proofs. For this reason we make a simplifying assumption $(1 - \phi)r_x > 2r$ that makes sure there is a pecking order: first priority is the project of bank x , then the interbank investment.

C Proofs

Proof. (**Proof of Lemma 1**)

Here we provide a general proof that allows for public liquidity $m \geq 0$. The proof of Lemma 1 can be obtained by replacing m with 0 below. It is easy to see that for a given portfolio profile (I_x, L, I_y) and a level of liquidity shortage $\zeta' = (\zeta - m - \Phi_x - \Phi_y)_+$, liquidations induced by the optimal behavior of x at the liquidation stage is given by

- If $\zeta' = 0$, nothing is liquidated.
- If $0 < \zeta' \leq \min\{I_x, I_y\}$, then
 - If $Lr \leq I_x r_x$, then I_y is liquidated.
 - If $Lr > I_x r_x$, then I_x is liquidated.
- If $\min\{I_x, I_y\} < \zeta' \leq \max\{I_x, I_y\}$, then $\max\{I_x, I_y\}$ is liquidated.
- If $\max\{I_x, I_y\} < \zeta'$, then both I_x and I_y are liquidated.

Then I_y does not get liquidated iff one of the following hold:

- $\zeta' = 0$
- $0 < \zeta' \leq \min\{I_x, I_y\}$ and $Lr > I_x r_x$

- $I_y < \zeta' \leq I_x$.

Then the expected profit of y is

$$\begin{aligned}\Pi_y(I_y) &= (F_{\zeta'}(0) + 1_{Lr > I_x r_x} (F_{\zeta'}(\min\{I_x, I_y\}) - F(0)) + 1_{I_x > I_y} (F_{\zeta'}(I_x) - F_{\zeta'}(I_y))) (I_y r_y - Lr) \\ &= \frac{\alpha}{Z} r_y \times \begin{cases} u_1(I_y) := \left(I_y - \frac{Lr}{r_y}\right) (Z_{\alpha, m} + D - I_y) & \text{if } Lr > I_x r_x \\ u_2(I_y) := \left(I_y - \frac{Lr}{r_y}\right) (Z_{\alpha, m} + D - 2I_y) & \text{on } I_x \geq I_y \text{ if } Lr \leq I_x r_x \\ u_3(I_y) := \left(I_y - \frac{Lr}{r_y}\right) (Z_{\alpha, m} + D - I_x - I_y) & \text{on } I_x \leq I_y \text{ if } Lr \leq I_x r_x \wedge I_x \leq L(1 - \phi) \end{cases}\end{aligned}$$

All of u_1, u_2, u_3 are concave quadratics. They are increasing up to their unique unconstrained arg max and decreasing afterwards. The unconstrained arg max of u_1, u_2, u_3 are given by

$$\begin{aligned}I_1^* &= \frac{1}{2} \left(Z_{\alpha, m} + D + \frac{Lr}{r_y} \right) \\ I_2^* &= \frac{1}{2} \left(\frac{Z_{\alpha, m} + D}{2} + \frac{Lr}{r_y} \right) \\ I_3^* &= \frac{1}{2} \left(Z_{\alpha, m} + D - I_x + \frac{Lr}{r_y} \right)\end{aligned}$$

Then $I_y^* = \arg \max \Pi_y(I_y)$ in these three regions are given by

$$\Pi_y(I_y^*) = \frac{\alpha}{Z} \begin{cases} u_1(\min\{L(1 - \phi), I_1^*\}) & \text{if } Lr > I_x r_x \\ u_2(\min\{L(1 - \phi), I_x, I_2^*\}) & \text{on } I_x \geq I_y \text{ if } Lr \leq I_x r_x \\ u_3(\max\{I_x, \min\{L(1 - \phi), I_3^*\}\}) & \text{on } I_x \leq I_y \text{ if } Lr \leq I_x r_x \wedge I_x \leq L(1 - \phi) \end{cases}$$

By Assumption 4, we have $L(1 - \phi) \leq I_3^*$. Also clearly $I_3^* \leq I_1^*$. Then

$$\min\{L(1 - \phi), I_1^*\} = \max\{I_x, \min\{L(1 - \phi), I_3^*\}\} = L(1 - \phi)$$

Then

$$\Pi_y(I_y^*) = \frac{\alpha}{Z} \begin{cases} u_1(L(1 - \phi)) & \text{if } Lr > I_x r_x \\ u_2(\min\{L(1 - \phi), I_2^*\}) & \text{on } I_x \geq I_y \text{ if } Lr \leq I_x r_x \wedge I_x \geq L(1 - \phi) \\ u_2(\min\{I_x, I_2^*\}) & \text{on } I_x \geq I_y \text{ if } Lr \leq I_x r_x \wedge I_x \leq L(1 - \phi) \\ u_3(L(1 - \phi)) & \text{on } I_x \leq I_y \text{ if } Lr \leq I_x r_x \wedge I_x \leq L(1 - \phi) \end{cases}$$

For the first case [if $Lr > I_x r_x$], $I_y^* = L(1 - \phi)$. For the second case [on $I_x \geq I_y$ if $Lr \leq$

$I_x r_x \wedge I_x \geq L(1 - \phi)$] note that $I_x \geq L(1 - \phi)$ implies both $I_x \geq I_y$ and $Lr \leq I_x r_x$. So this case can be restated as simply $[I_x \geq L(1 - \phi)]$. For the third and fourth cases jointly, we compare $u_2(\min\{I_x, I_2^*\})$ and $u_3(L(1 - \phi))$ under $[Lr \leq I_x r_x \wedge I_x \leq L(1 - \phi)]$. Note that

$$u_2(I_2^*) = \frac{1}{2} \left(\frac{Z_{\alpha,m} + D}{2} - \frac{Lr}{r_y} \right)^2$$

$$u_3(L(1 - \phi)) = \left(L(1 - \phi) - \frac{Lr}{r_y} \right) (Z_{\alpha,m} + D - I_x - L(1 - \phi))$$

Suppose $I_2^* < L(1 - \phi)$. Then we have $\frac{1}{2} \left(\frac{Z_{\alpha,m} + D}{2} + \frac{Lr}{r_y} \right) < L(1 - \phi)$, and so $\frac{1}{2} \left(\frac{Z_{\alpha,m} + D}{2} - \frac{Lr}{r_y} \right) < L(1 - \phi) - \frac{Lr}{r_y}$. Also $\left(\frac{Z_{\alpha,m} + D}{2} - \frac{Lr}{r_y} \right) < (Z_{\alpha,m} + D - I_x - L(1 - \phi))$. Thus, $u_2(\min\{I_x, I_2^*\}) \leq u_2(I_2^*) < u_3(L(1 - \phi))$. Now suppose $I_2^* \geq L(1 - \phi)$. Then by $I_x \leq L(1 - \phi)$ we have $I_2^* \geq I_x$. Then $u_2(\min\{I_x, I_2^*\}) = u_2(I_x)$. Recall that $u_2(I_x) = u_3(I_x)$, $L(1 - \phi) \leq I_3^*$, and u_3 is increasing up to I_3^* . Then we have $I_x \leq L(1 - \phi) \leq I_3^*$ and $u_3(I_x) \leq u_3(L(1 - \phi)) \leq u_3(I_3^*)$. Combining these we have $u_2(\min\{I_x, I_2^*\}) = u_2(I_x) = u_3(I_x) \leq u_3(L(1 - \phi))$. So in general, $u_2(\min\{I_x, I_2^*\}) \leq u_3(L(1 - \phi))$ and $I_y^* = L(1 - \phi)$ in the union of third and fourth cases, i.e. $[Lr \leq I_x r_x \wedge I_x \leq L(1 - \phi)]$. Therefore,

$$I_y^* = \begin{cases} \min\{L(1 - \phi), I_2^*\} & \text{if } I_x > L(1 - \phi) \\ L(1 - \phi) & \text{otherwise} \end{cases}$$

Under $I_x > L(1 - \phi)$ and Assumption 4, we have $L(1 - \phi) \leq I_2^*$ and so $I_y^* = L(1 - \phi)$.

Next consider the optimal portfolio of x . Let (I_x, L) be optimal and suppose that $I_x < L(1 - \phi)$. Then the expected profit of x is

$$\begin{aligned} \Pi_x &= F_{\zeta'}(0) (I_x r_x + Lr) \\ &\quad + (F_{\zeta'}(I_x) - F_{\zeta'}(0)) \max\{Lr, I_x r_x\} \\ &\quad + (F_{\zeta'}(L(1 - \phi)) - F_{\zeta'}(I_x)) I_x r_x \\ &\stackrel{(I_x, L)}{\propto} (Z_{\alpha,m} + D - I_x - L(1 - \phi)) (I_x r_x + Lr) \\ &\quad + I_x \max\{Lr, I_x r_x\} + (L(1 - \phi) - I_x) I_x r_x \end{aligned}$$

By $I_x < L(1 - \phi)$, right partial derivative w.r.t. I_x must be negative and left partial derivative w.r.t. L must be positive. If $I_x r_x \neq Lr$, these derivatives are given by the following: The F.O.C. w.r.t. I_x is

$$0 \geq - (I_x r_x + Lr) + r_x (Z_{\alpha,m} + D - I_x - L(1 - \phi))$$

$$\begin{aligned}
& + \begin{cases} Lr & \text{if } Lr > I_x r_x \\ 2I_x r_x & \text{if } Lr < I_x r_x \end{cases} \\
& + (L(1 - \phi) - 2I_x) r_x \\
& = r_x (Z_{\alpha, m} + D - 2I_x) - \begin{cases} 2I_x r_x & \text{if } Lr > I_x r_x \\ Lr & \text{if } Lr < I_x r_x \end{cases} \\
& \implies Z_{\alpha, m} + D \leq 2I_x + \begin{cases} 2I_x & \text{if } Lr > I_x r_x \\ \frac{Lr}{r_x} & \text{if } Lr < I_x r_x \end{cases}
\end{aligned}$$

The F.O.C. w.r.t. to L is

$$\begin{aligned}
0 & \leq - (1 - \phi) (I_x r_x + Lr) + r (Z_{\alpha, m} + D - I_x - L(1 - \phi)) \\
& + \begin{cases} I_x r & \text{if } Lr > I_x r_x \\ 0 & \text{if } Lr < I_x r_x \end{cases} \\
& + (1 - \phi) I_x r_x \\
& = r (Z_{\alpha, m} + D - I_x - 2L(1 - \phi)) \\
& + \begin{cases} I_x r & \text{if } Lr > I_x r_x \\ 0 & \text{if } Lr < I_x r_x \end{cases} \\
& \implies Z_{\alpha, m} + D \geq I_x + 2L(1 - \phi) - \begin{cases} I_x r & \text{if } Lr > I_x r_x \\ 0 & \text{if } Lr < I_x r_x \end{cases}
\end{aligned}$$

Combining the two, we get

$$\begin{aligned}
& 2I_x + \begin{cases} 2I_x & \text{if } Lr > I_x r_x \\ \frac{Lr}{r_x} & \text{if } Lr < I_x r_x \end{cases} \\
& \geq I_x + 2L(1 - \phi) - \begin{cases} I_x r & \text{if } Lr > I_x r_x \\ 0 & \text{if } Lr < I_x r_x \end{cases} \\
& \implies 0 \leq I_x - 2L(1 - \phi) + \begin{cases} 3I_x & \text{if } Lr > I_x r_x \\ \frac{Lr}{r_x} & \text{if } Lr < I_x r_x \end{cases}
\end{aligned}$$

Under $Lr < I_x r_x$, we get

$$0 \leq I_x - 2L(1 - \phi) + \frac{Lr}{r_x} < I_x - 2L(1 - \phi) + I_x < 0$$

So we must have $Lr > I_x r_x$. Then $2I_x \geq L(1 - \phi)$. But then $2I_x r_x \geq L(1 - \phi)r_x > 2Lr$, by Assumption 5. Hence $I_x r_x > Lr$. This is a contradiction.

So we must have $I_x r_x = Lr$. This implies that $I_x \neq 0$. Then the right partial derivative of the profit w.r.t. I_x must be negative and left partial derivative of the profit w.r.t. I_x must be positive. In particular, the right derivative is

$$r_x (Z_{\alpha,m} + D - 2I_x) - Lr$$

and the left derivative is

$$r_x (Z_{\alpha,m} + D - 2I_x) - 2I_x r_x$$

Then the left derivative is smaller than the right derivative. Contradiction. So the optimal portfolio satisfies $I_x \geq L(1 - \phi) = L - \Phi_y$. By $(1 - \phi)r_x > r$ this further implies that $I_x r_x > Lr$. $\square$

Proof. (Proof of Proposition 1 and Proposition 2)

Proposition 1 is simply a corollary of Proposition 2, obtained by replacing m with 0, so we provide the proof for Proposition 2. By the proof of Lemma 1 above, which allows for $m \geq 0$, we have $\Phi_y = L\phi$ and $I_x > L(1 - \phi)$. Then the ex-post profit for bank x is given by

$$\pi_x = \begin{cases} I_x r_x + Lr & \text{if } 0 \leq \zeta \leq m + \Phi_x + L\phi \\ I_x r_x & \text{if } m + \Phi_x + L\phi < \zeta \leq m + \Phi_x + L \\ Lr & \text{if } m + \Phi_x + L < \zeta \leq m + \Phi_x + L\phi + I_x \\ 0 & \text{if } m + \Phi_x + L\phi + I_x < \zeta \end{cases}$$

The expected profit is

$$\Pi_x \underset{(I_x, L)}{\propto} r_x (Z_{\alpha,m} + D - I_x) I_x + 2(1 - \phi)r \left(\frac{Z_{\alpha,m} + D}{2(1 - \phi)} - L \right) L$$

The unconstrained maximizer is

$$L = \frac{Z_{\alpha,m} + D}{4(1 - \phi)}, \quad I_x = \frac{Z_{\alpha,m} + D}{2}$$

At these values, $L, I_x \geq 0$ and $I_x \geq L(1 - \phi)$ hold. The remaining constraint is

$$D \geq L + I_x \iff \alpha \geq \frac{Z}{Z + D \left(\frac{1-2\phi}{3-2\phi} \right) - m}$$

(Note that this lower bound is less than $\bar{\alpha}$ for $m = 0$ if $\frac{r}{r_y} \geq \frac{2(1-2\phi)(1-\phi)}{3-2\phi}$, which makes this region of parameters is non-empty for $m = 0$. This guarantees that the following regions are also non-empty for $m = 0$. As m grows, it is natural that some regions become obsolete in the pecking order.)

Next consider $\alpha < \frac{Z}{Z + D \left(\frac{1-2\phi}{3-2\phi} \right) - m}$ ($D \frac{1-2\phi}{3-2\phi} < Z_{\alpha,m}$). The constraint $I_x + L \leq D$ binds. Under constraint $I_x = D - L \in [0, D]$, the FOC gives

$$\frac{d\Pi_x}{dL} = 0 \implies I_x = \frac{D(4(1-\phi)r + r_x - r) + Z_{\alpha,m}(r_x - r)}{2(r_x + 2(1-\phi)r)}$$

As $r_x > r$ we have $L \leq D$ and $I_x \geq 0$. On the other hand

$$L \geq 0 \iff \alpha \geq \frac{Z}{Z + D \frac{r_x+r}{r_x-r} - m}$$

This also ensures $I_x \leq D$. The last constraint $I_x \geq L(1 - \phi)$ holds trivially.

Finally, under $\alpha < \frac{Z}{Z + D \left(\frac{r_x+r}{r_x-r} \right) - m}$ ($D \frac{r_x+r}{r_x-r} < Z_{\alpha,m}$), we have $L = 0$ and $I_x = D$.

Summarizing:

1. If $\bar{\alpha} \geq \alpha > \frac{Z}{Z + D \left(\frac{1-2\phi}{3-2\phi} \right) - m}$ ($D \frac{1-2\phi}{3-2\phi} \geq Z_{\alpha,m}$),

$$I_x = \frac{D + Z_{\alpha,m}}{2}, \quad L = \frac{D + Z_{\alpha,m}}{4(1-\phi)}, \quad \Phi_x = D - I_x - L > 0$$

2. If $\frac{Z}{Z + D \left(\frac{1-2\phi}{3-2\phi} \right) - m} > \alpha > \frac{Z}{Z + D \left(\frac{r_x+r}{r_x-r} \right) - m}$ ($D \frac{r_x+r}{r_x-r} > Z_{\alpha,m} > D \frac{1-2\phi}{3-2\phi}$) then

$$I_x = \frac{D(4(1-\phi)r + r_x - r) + Z_{\alpha,m}(r_x - r)}{2(r_x + 2(1-\phi)r)}$$

$$L = \frac{D(r_x + r) - Z_{\alpha,m}(r_x - r)}{2(r_x + 2(1-\phi)r)}, \quad \Phi_x = 0$$

3. If $\frac{Z}{Z + D \left(\frac{r_x+r}{r_x-r} \right) - m} > \alpha$ ($Z_{\alpha,m} > D \frac{r_x+r}{r_x-r}$), then

$$I_x = D, \quad L = 0, \quad \Phi_x = 0.$$

□

Proof. (Proof of Proposition 3) Note that there is some inconsequential multiplicity in the amount of ex-post short term borrowing. As the short-term borrowing is risk-free in the model, for simplicity, we have assumed away interest on it. For robustness, we assume the smallest amount of short-term borrowing to meet the shock takes place. If $\zeta < \Phi_x$, there is no need for short-term borrowing. For $\Phi_x < \zeta \leq \Phi_x + \Phi_y + m$, y can lend the shortage $\zeta - \Phi_x$ to x to avoid liquidations. If $\zeta > \Phi_x + \Phi_y + m$, liquidation is inevitable. If $\Phi_x + L + m > \zeta > \Phi_x + \Phi_y + m$, x liquidates L . This gives L extra liquidity to x on top of its reserves Φ_x . Bank x can still borrow m from y in this case. But if $\zeta < L + \Phi_x$, x does not need to borrow from y . Only when $\zeta > L + \Phi_x$, there is borrowing from y at the amount of shortage $\zeta - L - \Phi_x$. Therefore, when $\Phi_x + L + m > \zeta > \max\{\Phi_x + \Phi_y + m, L + \Phi_x\}$, there is $\zeta - L - \Phi_x$ borrowing. Continuing with the same logic, we find that the ex-post amount of short-term borrowing by x from y under m is given by

$$b = \begin{cases} \zeta - \Phi_x & \text{if } \Phi_x < \zeta \leq \Phi_x + \Phi_y + m \\ \zeta - L - \Phi_x & \text{if } \Phi_x + \max\{L, \Phi_y + m\} < \zeta \leq \Phi_x + L + m \\ \zeta - I_x - \Phi_x & \text{if } \Phi_x + \max\{I_x, L + m\} < \zeta \leq \Phi_x + I_x + \Phi_y + m \\ 0 & \text{otherwise} \end{cases}$$

The expectation of this w.r.t. ζ is

$$B = \frac{\alpha}{Z} (2(m + \Phi_y)^2 + m^2 - \max\{0, m + \Phi_y - L\}^2 - \max\{0, m + L - I_x\}^2)$$

Under $D^{\frac{1-2\phi}{3-2\phi}} \geq Z_{\alpha,m}$, this is

$$B = \frac{\alpha}{2Z} (2(m + \Phi_y)^2 + m^2 - \max\{0, m - (1 - \phi)L\}^2 - \max\{0, m - (1 - 2\phi)L\}^2)$$

Note that $D^{\frac{1-2\phi}{3-2\phi}} \geq Z_{\alpha,m}$ implies $L = \frac{D+Z_{\alpha,m}}{4(1-\phi)} > \frac{Z_{\alpha,m}}{1-2\phi} > \frac{m}{1-2\phi}$. So $B = \frac{\alpha}{2Z} (2(m + \Phi_y)^2 + m^2)$ which is increasing in m .

For the case of $D^{\frac{1-2\phi}{3-2\phi}} < Z_{\alpha,m}$, note that B is continuous in m . Also, the negative terms $\max\{0, m + \Phi_y - L\}$ and $\max\{0, m + L - I_x\}$ are increasing in m . So if

$$2(m + \Phi_y)^2 + m^2 - (m + \Phi_y - L)^2 - (m + L - I_x)^2$$

is increasing in m , then B is increasing in m . The derivative of this expression w.r.t. m is 2

times

$$2(m + \Phi_y) \left(1 + \phi \frac{dL}{dm}\right) + m - (m + \Phi_y - L) \left(1 - (1 - \phi) \frac{dL}{dm}\right) - (m + L - I_x) \left(1 + \frac{dL}{dm} - \frac{dI_x}{dm}\right)$$

Under $Z_{\alpha,m} > D \frac{r_x+r}{r_x-r}$ this is

$$2(m + \Phi_y) + m - (m + \Phi_y - L) - (m + L - I_x) = m + \Phi_y + I_x > 0$$

Under $D \frac{r_x+r}{r_x-r} > Z_{\alpha,m} > D \frac{1-2\phi}{3-2\phi}$ this is

$$\begin{aligned} & 2(m + \Phi_y) \left(1 + \phi \frac{dL}{dm}\right) + m - (m + \Phi_y - L) \left(1 - (1 - \phi) \frac{dL}{dm}\right) - (m + 2L - D) \left(1 + 2 \frac{dL}{dm}\right) \\ & > D \left(1 - \frac{r_x - r}{r_x + 2(1 - \phi)r}\right) + L \left(\frac{(5 - 2\phi)(r_x - r)}{2(r_x + 2(1 - \phi)r)} - (1 - \phi)\right) > 0 \end{aligned}$$

Thus, B is continuous and increasing. $\square$

Proof. (Proof of Proposition 4)

Now there is θ probability that x_i gets a shock. Then Proposition 1 goes through by replacing α with θ . Note that $\frac{Z}{Z+D\left(\frac{1-2\phi}{3-2\phi}\right)-m} > \frac{1}{2} > \theta$ so we do not have the region in which $\Phi_{x_i} > 0$.

Now suppose that the the core banks can borrow each others reserves. We assume $Z > 2D+m$ so that the shock can always be larger than the total cash in the system and we can avoid corner cases. For the pair i , the cash reserves of y_i act as an addition to m . Also note that x_i and x_j do not keep reserves and so we do not need to worry about x_i short-term lending to y_i and y_i intermediating this to y_j . Thus, for x_i , the best response is given by

$$L_i = \left(\frac{D(r_x + r) - (Z_{\theta,m} + L_j\phi)(r_x - r)}{2(r_x + 2(1 - \phi)r)} \right)_+$$

The symmetric equilibrium is given by

$$L = \left(\frac{D(r_x + r) - (Z_{\theta,m} + L\phi)(r_x - r)}{2(r_x + 2(1 - \phi)r)} \right)_+$$

1. If $\frac{1}{2} > \theta > \frac{Z}{Z+D\left(\frac{r_x+r}{r_x-r}\right)-m}$ ($D \frac{r_x+r}{r_x-r} > Z_{\theta,m}$) then

$$L_{x_i} = \frac{D(r_x + r) - Z_{\theta,m}(r_x - r)}{2(r_x + 2(1 - \phi)r) + \phi(r_x - r)}, \quad I_x = D - L$$

2. If $\frac{Z}{Z+D\frac{(r_x+r)}{(r_x-r)}-m} > \theta$, ($D\frac{r_x+r}{r_x-r} < Z_{\theta,m}$) then

$$L_{x_i} = 0, \quad I_{x_i} = D$$

□

Proof. (Proof of Lemma 2)

For $D\frac{r_x+r}{r_x-r} < Z_{\theta,m}$, $L_C = L_D = 0$. There is no network. So consider the region $D\frac{r_x+r}{r_x-r} > Z_{\theta,m}$. From the earlier analysis we know that if both banks connect to their regional correspondents, in equilibrium,

$$\frac{Z}{\alpha} \Pi_{x_i}^C = (Z_{\theta,m} + D - I_x) I_x r_x + (Z_{\theta,m} + D - 2(1 - \phi)L) Lr$$

where

$$L_C = \frac{D(r_x + r) - Z_{\theta,m}(r_x - r)}{2(r_x + 2(1 - \phi)r)}$$

If both regions connect to NY, in equilibrium,

$$\frac{Z}{\alpha} \Pi_{x_i}^N = (Z_{\theta,m} + \phi L + D - I_x) I_x r_x + (Z_{\theta,m} + \phi L + D - 2(1 - \phi)L) Lr - c(L)$$

where

$$L_N = \frac{D(r_x + r) - Z_{\theta,m}(r_x - r)}{2(r_x + 2(1 - \phi)r) + \phi(r_x - r)}$$

Note

$$\frac{d\left(\frac{Z}{\alpha} \Pi_{x_i}^C\right)}{dm} = I_{x,C} r_x + L_C r$$

and

$$\frac{d\left(\frac{Z}{\alpha} \Pi_{x_i}^N\right)}{dm} = (I_{x,N} r_x + L_N r) \left(1 + \phi \frac{dL_N}{dm}\right)$$

Denote $A = 2(r_x + 2(1 - \phi)r)$ and $B = D(r_x + r) - Z_{\theta,m}(r_x - r)$. Then

$$\begin{aligned} \frac{Z}{\alpha} \frac{d(\Pi_{x_i}^C)}{dm} &= Dr_x - (r_x - r) \frac{B}{A} \\ \frac{Z}{\alpha} \frac{d(\Pi_{x_i}^N)}{dm} &= \left(Dr_x - (r_x - r) \frac{B}{A + \phi(r_x - r)} \right) \left(\frac{A}{A + \phi(r_x - r)} \right) \end{aligned}$$

$$\begin{aligned}\frac{Z}{\alpha} \left(\frac{d(\Pi_{x_i}^C)}{dm} - \frac{d(\Pi_{x_i}^N)}{dm} \right) &= Dr_x - (r_x - r) \frac{B}{A} \\ &> \frac{Dr(r_x - r)\phi}{A + \phi(r_x - r)} > 0\end{aligned}$$

□

Proof. (Proof of Proposition 5)

Since the difference in the derivative is bounded away from zero, as m grows, $\Pi_{x_i}^C$ exceeds $\Pi_{x_i}^N$ eventually. The switching point m_c depends on the fixed cost c as well. If the cost c is very large, the stable network is regional for all m . In this case, $m_c = D \frac{r_x + r}{r_x - r} - Z \frac{1 - \theta}{\theta}$. If c is very small, the stable network is central for all m . Then $m_c = 0$. In between as c grows, m_c grows from 0 to $D \frac{r_x + r}{r_x - r} - Z \frac{1 - \theta}{\theta}$.

□

Proof. (Proof of Proposition 6)

Now suppose that m is independently drawn from distribution F_m with support $[0, \bar{m}]$ and mean m^* . Assume $\bar{m} < Z - D$. In principle, stochastic m could complicate the algebra dramatically. But, as the shocks can always be larger than liquidity, all results regarding portfolios still hold with m^* instead of m . In order to formalize this, go back to the liquidations induced by the optimal behavior of x after the shock, as outlined in the proof of Lemma 1. The last region of the shock where both project are liquidated is given by $\max\{I_x, I_y\} < \zeta' = \zeta - m - \Phi_x - \Phi_y$. This is, $\zeta > \max\{I_x, I_y\} + m + \Phi_x + \Phi_y$. By $\bar{m} < Z - D$,

$$\max\{I_x, I_y\} + m + \Phi_x + \Phi_y < \max\{I_x, I_y\} + Z - D + \Phi_x + \Phi_y < Z$$

Therefore, there is positive probability that both project get liquidated regardless of the portfolio. So all regions of shocks in the cases for liquidations have positive probability. Then the expected payoffs are given by

$$\begin{aligned}\frac{Z}{\alpha} \mathbb{E}_m [\Pi_x] &= (Z_{\alpha,0} + m^* + D - I_x - I_y) (I_x r_x + Lr) + \min\{I_x, I_y\} \max\{Lr, I_x r_x\} \\ &\quad + (\max\{I_x, I_y\} - \min\{I_x, I_y\}) \min\{I_x, I_y\} r_{\arg \min_z I_z} \\ \frac{Z}{\alpha} \mathbb{E}_m [\Pi_x] &= (I_y r_y - Lr) \left[(Z_{\alpha,0} + m^* + D - I_x - I_y) + \mathbf{1}_{I_x r_x < Lr} \min\{I_x, I_y\} \right. \\ &\quad \left. + \mathbf{1}_{I_x < L} (\max\{I_x, I_y\} - \min\{I_x, I_y\}) \right]\end{aligned}$$

So the solution is identical, just by replacing m with m^* now. For closed form results we suppose that m is 0 w.p. β and $U[0, \frac{2m^*}{1-\beta}]$ w.p. $1 - \beta$ where $m^* < \frac{1-\beta}{2}(Z - D)$. Note that this has mean m^* .

We first consider the event that all funded projects get liquidated, which we call systemic risk. This is, $\zeta' > I_x$. (Under $D \frac{r_x+r}{r_x-r} \geq Z_{\alpha, m^*}$ y 's project is indeed funded. Otherwise, the only funded project is x 's.) Systemic risk is

$$\begin{aligned} & \frac{\alpha}{Z} (Z - D + (1 - \phi)L - m^*) \\ & \propto_{(m^*, \beta)} - m^* + (1 - \phi) \begin{cases} \frac{D + Z_{\alpha, m^*}}{4(1 - \phi)} & \text{if } D \frac{1-2\phi}{3-2\phi} \geq Z_{\alpha, m^*} \\ \frac{D(r_x+r) - (r_x-r)Z_{\alpha, m^*}}{2(r_x+2(1-\phi)r)} & \text{if } D \frac{r_x+r}{r_x-r} > Z_{\alpha, m^*} > D \frac{1-2\phi}{3-2\phi} \\ 0 & \text{if } Z_{\alpha, m^*} > D \frac{r_x+r}{r_x-r} \end{cases} \end{aligned}$$

The first term $-m^*$ is the direct effect of the availability of public liquidity. This has a natural effect of reducing the risk of liquidations. The second term after the bracket is the equilibrium effect of public liquidity. The availability of public liquidity influences the availability of private liquidity in the system through the portfolio choices, in particular, through L . The equilibrium effect increases in m^* up to $D \frac{1-2\phi}{3-2\phi} - Z_{\alpha, 0}$ and decreases afterwards. The net effect is always to reduce systemic risk.

Next consider contagion risk, the probability that the project of y gets liquidated. This event is the union of $\zeta' > I_x$ (systemic risk) and $0 < \zeta' \leq L(1 - \phi)$, “only-contagion.” The probability of only-contagion is $\frac{\alpha}{Z}L(1 - \phi)$. This is increasing in m^* for $m^* < D \frac{1-2\phi}{3-2\phi} - Z_{\alpha, 0}$ and decreasing afterwards m^* . We have calculated systemic risk, and contagion risk is

$$\frac{\alpha}{Z} (Z - D + 2(1 - \phi)L - m^*) \propto_{(m^*, \beta)} 2(1 - \phi)L - m^*$$

This is always decreasing in m^* .

Now consider direct risk, the probability that the project of x gets liquidated. This event is given by $L(1 - \phi) < \zeta'$. The part $I_x < \zeta'$ is the systemic risk. The part of $L(1 - \phi) < \zeta' \leq I_x$ is “only-direct-risk.” Only-direct-risk is given by

$$\begin{aligned} & \frac{\alpha}{Z} (I_x - L(1 - \phi)) \\ & \propto_{(m^*, \beta)} \begin{cases} \frac{D + Z_{\alpha, m^*}}{4} & \text{if } D \frac{1-2\phi}{3-2\phi} \geq Z_{\alpha, m^*} \\ \frac{D(3(1-\phi)r - r + \phi r_x) + (2-\phi)(r_x-r)Z_{\alpha, m^*}}{2(r_x+2(1-\phi)r)} & \text{if } D \frac{r_x+r}{r_x-r} > Z_{\alpha, m^*} > D \frac{1-2\phi}{3-2\phi} \\ D & \text{if } Z_{\alpha, m^*} > D \frac{r_x+r}{r_x-r} \end{cases} \end{aligned}$$

This is always increasing in m^* . The public liquidity always increases the only-direct-risk. This is perhaps particularly relevant for the Great Depression. The combined direct-risk to x is

$$\frac{\alpha}{Z} (Z - D + (1 - \phi)L - m^* + I_x - L(1 - \phi))$$

$$\underset{(m^*, \beta)}{\propto} - m^* + \begin{cases} \frac{D + Z_{\alpha, m^*}}{2} & \text{if } D \frac{1-2\phi}{3-2\phi} \geq m^* + Z_{\alpha, 0} \\ \frac{D(4(1-\phi)r + r_x - r) + Z_{\alpha, m^*}(r_x - r)}{2(r_x + 2(1-\phi)r)} & \text{if } D \frac{r_x + r}{r_x - r} > m^* + Z_{\alpha, 0} > D \frac{1-2\phi}{3-2\phi} \\ D & \text{if } m^* + Z_{\alpha, 0} > D \frac{r_x + r}{r_x - r} \end{cases}$$

This is always decreasing in m^* . The public liquidity always reduces the direct-risk to x .

Finally, we consider vulnerability, that is, the risks conditional on $m = 0$. Systemic vulnerability is given by

$$\frac{\alpha}{Z} (Z - D + (1 - \phi)L)$$

This is increasing in m^* for small m^* and decreasing for large m^* . Contagion vulnerability is

$$\frac{\alpha}{Z} (Z - D + 2(1 - \phi)L)$$

also increasing in m^* for small m^* and decreasing for large m^* . Direct vulnerability is

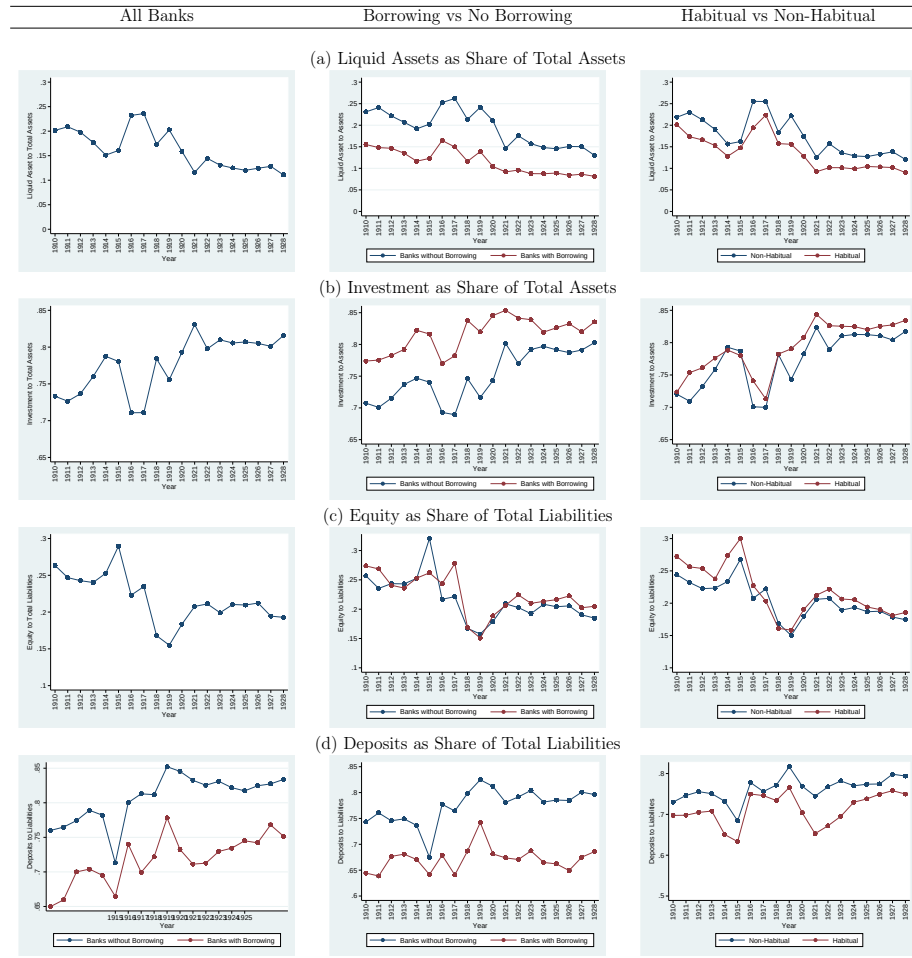
$$\frac{\alpha}{Z} (I_x - L(1 - \phi))$$

always increasing in m^* . □

D Online Appendix: State Bank Balance Sheet Data from Call Reports

In the main text, we provide summary statistics of the Virginia state bank balance sheet data from *Annual Report of the Banking Division of the State Corporation Commission*. In Figure D3, we plot the movement of balance sheet ratios from 1910 to 1928. Figure D3 shows that balance sheet ratios displayed irregular patterns between 1914 and 1921 due to the changes in reserve requirements and the implementation of monetary policy to accommodate WWI. Hence, we focus on the periods 1910-1913 and 1920-1928.

Table D3: Balance Sheet Ratios, 1910-1928



Notes: Liquid assets include vault cash and interbank deposits. Investments are comprised of loans and bonds. Short-term borrowing is comprised of rediscounts and bills payable.

Source: *Statements Showing the Condition of the Incorporated State Banks operating in Virginia*.

E Online Appendix: Aggregate Balance Sheet Information

In the main text, we provide summary statistics of the balance sheet data aggregated at the state level from *Annual Report of the Comptroller of the Currency*. In Figure E3, we plot the movement of balance sheet ratios from 1910 to 1928. Figure E3 shows that in the 1920s, short-term borrowing increased and liquid assets declined.

Figure E3: Aggregate Balance Sheet Ratios, 1910-1928

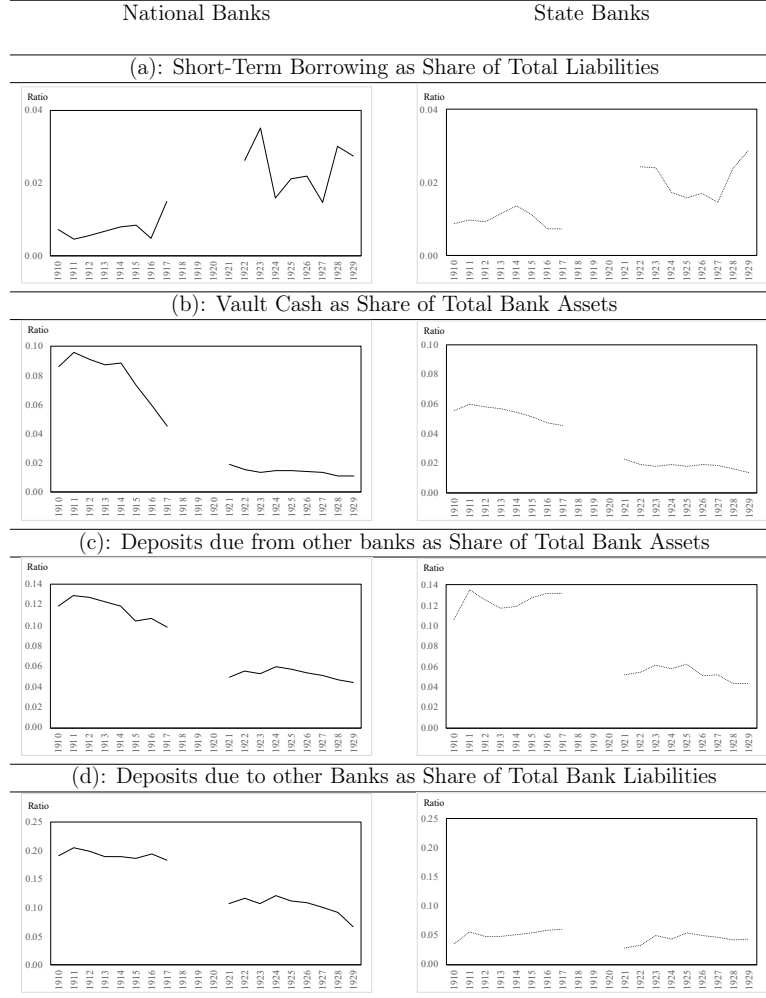


Figure E3 plots the ratio of short-term borrowing to total liabilities for national and state banks. All data are aggregated by the OCC: data for national banks are aggregated across all states, 17 reserve cities, and 3 central-reserve cities; data for state banks are aggregated across all states, all reserve cities, and reserve cities.

Source: *Annual Report of the Comptroller of the Currency*.

In addition, we check the robustness of our findings by restricting the data in two dimensions. First, we restrict our sample using state bank participation rate, as states with financial

and manufacturing sectors displayed a higher proportion of state bank membership than agricultural states. Given the irregular geographic distribution of membership, one might be concerned that the described changes were generated by state member banks and that therefore our classifying all state banks as nonmembers clutters the analysis. To alleviate this concern, we restrict our sample and compare the asset composition of member and nonmember banks only in states where the membership ratio of state banks was under 10% in 1920.

Second, we restrict our sample using state-level reserve requirements. Changes in the liquidity of the state banking system might be driven by changes in reserve requirements by state regulators rather than by voluntary liquidity changes. To rule out this possibility, we divided states into three groups: (1) states that decreased their reserve requirements, (2) states that increased their reserve requirements, and (3) states that did not change their reserve requirements. Between 1910 and 1929, 22 states reduced reserve requirements, 10 states increased reserve requirements, and 16 states kept reserve requirements unchanged.³⁰

For states where the state bank participation rate was below 10%, Figure E4 plots the fraction of total assets that state banks in those states held in borrowing, cash, and interbank deposits. In all cases, and regardless of the change in reserve requirements, nonmember banks reduced cash and interbank deposits and increased borrowing after the Federal Reserve came into existence (in 1914).

To summarize, we find that the existence of the Federal Reserve reduced liquidity (in the form of cash and interbank deposits) and intensified interbank relations (in the form of higher short-term borrowing) for both member and nonmember banks. Furthermore, member banks significantly reduced their relations with other member banks, but not their relations with nonmember banks. These factors suggest less private cross-insurance but still exposure to withdrawals, which contributed to the possibility of more contagion and greater vulnerability of the financial system.

³⁰See White (2014) for information on state reserve requirements. We classify CA, DE, GA, IN, KS, KY, LA, MI, MN, MT, NM, NY, OK, OR, PA, SD, TX, VA, WA, WI, WV as states with decreasing reserve requirements. In addition, we classify AR, CO, IA, MD, MS, NH, SC, TN, VT, WY as states with increasing reserve requirements. Last, we classify AL, CT, FL, ID, IL, MA, ME, MO, NC, ND, NE, NJ, NV, OH, OK, UT as states that did not change reserve requirements.

Figure E4: Bank Liquidity and Changes in State-Level Reserve Requirements, 1910-1928

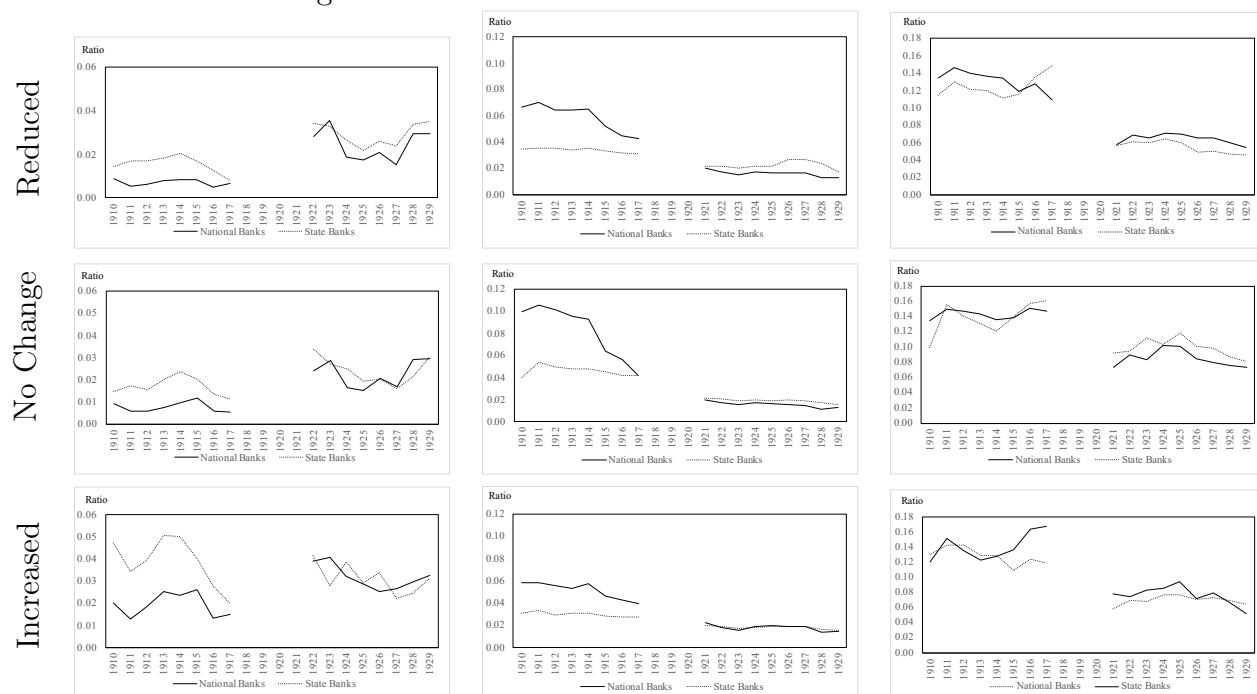


Figure E4 the share of short-term borrowing against total liabilities, the share of vault cash against total assets, and the share of deposits due from other banks against total assets for states with different reserve requirements. Data are further restricted for states where the Federal Reserve membership ratio of state banks was under 10% in 1920. All data are aggregated by the OCC: data for national banks are aggregated across all states, 17 reserve cities, and 3 central-reserve cities; data for state banks are aggregated across all states, all reserve cities, and reserve cities.

Source: *Annual Report of the Comptroller of the Currency*.