

## Bank Networks and Systemic Risk: Evidence from the National Banking Acts<sup>†</sup>

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*The National Banking Acts (NBAs) of 1863–1864 established rules governing the amounts and locations of interbank deposits, thereby reshaping the bank networks. Using unique data on bank balance sheets and detailed interbank deposits in 1862 and 1867 in Pennsylvania, we study how the NBAs changed the network structure and quantify the effect on financial stability in an interbank network model. We find that the NBAs induced a concentration of interbank deposits at both the city and bank levels, creating systemically important banks. Although the concentration facilitated diversification, contagion would have become more likely when financial center banks faced large shocks. (JEL E44, G01, G21, G28, L14, N21)*

The financial crisis of 2007–2009 showed how the interconnectedness among financial institutions could pose systemic risk to the financial system. When a highly interconnected institution becomes distressed, as happened with Lehman Brothers, its counterparties may also experience losses and limited access to liquidity. In response, economists and policymakers have attempted to understand how to regulate networks and contain systemic risk. Despite extensive studies on the roles of regulations (Allen and Gale 2007) and networks (e.g., Elliott, Golub, and Jackson 2014; Acemoglu, Ozdaglar, and Tahbaz-Salehi 2015) separately, little has been done in jointly examining how regulations of networks affect systemic risk.

Several challenges limit existing studies. One notable difficulty originates from the lack of detailed, comprehensive data on the structure of financial networks, particularly over periods of significant regulatory change. With limited information on the topology of financial networks, it is difficult to assess systemic susceptibility to

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contagion. Also, it is challenging to disentangle counterparty exposures arising from various instruments.

In this paper, we tackle the challenges by exploiting the passage of the National Banking Acts (NBAs) of 1863 and 1864. The NBAs established legal reserve requirements that allowed banks to maintain a large portion of interbank deposits in designated cities, thereby creating a reserve pyramid. Under the newly enforced reserve requirements, New York City took a special role as the *central reserve city*. Regional financial centers were designated as *reserve cities*.<sup>1</sup> Rural banks outside of central reserve and reserve cities were called *country banks*. They deposited reserves at reserve city banks which in turn deposited reserves in New York City. The requirements significantly changed the pattern of linkages across banks in a short period.

We examine how this banking reform changed the structure of bank networks and the stability of the banking system. Our first contribution is to document how the NBAs had reshaped the interbank network using unique data on bank balance sheets and interbank deposits. Our second contribution is to perform a counterfactual analysis using the NBAs as an exogenous change in the network. In particular, we perform “stress tests” on the network to assess how the transmission of liquidity shocks differs due to a change in regulation. This exercise sheds light on how an important regulatory reform would affect the extent and nature of financial fragility.

The banking system around the passage of the NBAs provides us a unique setting to examine systemic risk arising from bank networks. First, to overcome the data challenges, we construct a dataset of banks in Pennsylvania and New York City that are listed in the annual report of state banks and examination reports of national banks for the years 1862 and 1867. The data provide information on individual correspondent relationships, giving us a fuller picture of the topology of the bank networks during that period. The state banking reports provide detailed information on the amounts “due from other banks” by individual debtor banks on the asset side of the balance sheet. Similarly, the examination reports list the amount of interbank deposits due from each legal correspondent. Such detailed information allows us to identify the topology of the interbank networks and provides us a measure of the intensity of these relationships.<sup>2</sup>

Second, the simple structure of the US banking industry during this period helps us identify risk channels. While financial institutions today have various types of counterparty exposures due to a wide variety of financial instruments held by numerous parties, banks in the mid-to-late 1800s faced counterparty exposure solely because of interbank deposits. Moreover, the introduction of the NBA legislation offers us an opportunity to observe the structural evolution of the interbank network.

We document two key features of the interbank network before the NBAs. First, the interbank network already exhibited a core-periphery structure as rural banks

<sup>1</sup>The National Banking Act of 1863 created nine large reserve cities, i.e., Baltimore, Boston, Chicago, Cincinnati, New Orleans, New York City, Philadelphia, Providence, and St. Louis. The National Banking Act of 1864 restructured the previous reserve requirements. The number of reserve cities increased to 16. New reserve cities (Albany, Cleveland, Detroit, Leavenworth, Louisville, Milwaukee, Pittsburgh, San Francisco, and Washington) were added, and Providence was dropped. In addition, New York City was designated a central reserve city.

<sup>2</sup>We refer to banks placing deposits in other banks as *respondents* and banks providing the services as *correspondents*. We use the terms “correspondent networks” and “interbank networks” interchangeably throughout the paper.

dealt exclusively with banks in financial centers. Many banks placed deposits in New York City and Philadelphia; they also used banks in other regional financial centers such as Harrisburg and Scranton in Pennsylvania. Second, correspondent deposit markets in New York City and Philadelphia were of comparable magnitude, indicating that Philadelphia was an important financial center that likely served as the ultimate repository destination of interbank deposits, much like New York City.

We find that the reserve pyramid with three distinct tiers emerged as new reserve requirements were enforced after the NBAs. This pattern arose because interbank deposits became heavily concentrated in cities designated as reserve and central reserve cities. First, New York City became the ultimate destination of interbank deposits. The size of correspondent deposits in New York City grew ten times larger than those in Philadelphia. Second, Pittsburgh emerged as a new financial center after it was designated as a reserve city. At the same time, other regional centers experienced a reduction in the interbank deposits replaced by rural banks. Third, banks in financial centers increased their cash holdings to create larger liquidity buffers in the event of deposit withdrawals.

To examine how the concentration of interbank deposits at reserve and central reserve cities would have affected the stability of the banking system and the extent of contagion, we build a network model of interbank deposits. The model embeds liquidity withdrawals in the interbank payment system introduced by Eisenberg and Noe (2001). In this two-period model, banks may experience runs and asset liquidation due to a maturity mismatch between short-term liquid liabilities and long-term illiquid asset investments. Such a framework allows us to study the impact of banking panics due to deposit withdrawals, by both retail and institutional depositors.

We then calibrate the model and simulate two types of banking crises to compare systemic risk measures before and after the rule change. First, we investigate how investment losses of New York City banks would have affected the rest of the financial system. To simulate such crises, we reduce the expected investment returns of New York City banks. Second, we examine the role of liquidity shortages at banks outside financial centers. Country banks withdraw deposits from their city correspondents, which in turn experience liquidity shortages and liquidate their loans. For each simulated scenario, we measure the probability of joint liquidations among banks and compare the resilience of the banking system before and after the NBAs.

Our results from the counterfactual exercises show that the banking system after the NBAs would have been “robust-yet-fragile” as interbank deposits became concentrated. The system would have become more robust as long as the most connected institutions had not faced large liquidity shocks. However, when expected losses were large enough to trigger massive withdrawals and liquidation at the most connected New York City banks, interbank connections would have served as channels for contagion. Financial center banks would have failed to repay deposits in full to their respondents, thereby causing runs and systemic liquidation. On the other hand, the concentrated interbank network after the NBAs would have been more resilient to liquidity shocks originating from banks outside financial centers. Although the interbank linkages would pass on contagious withdrawals upwards along the pyramid, financial center banks could have been liquid enough to meet such demand.

Our findings suggest that financial stability depends crucially on the concentration of links, the composition of bank balance sheets, and the magnitude of shocks. The mechanism works as follows. A more concentrated network is more robust to mild shocks because risk diversification dominates contagion: since a financial center bank has a greater number of depositors, each depositor bears only a small fraction of the shortfall. In contrast, such a system is more fragile when the financial center banks face large shocks: large losses at the most connected institutions enable the transmission of liquidity shocks to a large number of counterparties simultaneously, thereby increasing the likelihood of systemic liquidation events. In this case, concentrated links facilitate contagion. This “robust-yet-fragile” nature of the post-NBAs interbank network echoes the “knife-edge flipping” concept described in Haldane (2013) and the theoretical findings of Acemoglu, Ozdaglar, and Tahbaz-Salehi (2015) and Gai and Kapadia (2010).

This study provides new insights into financial regulations related to the architecture of the financial system. One of the key proposals for regulatory reform following the financial crisis of 2007–2009 is the mandatory clearing of standardized over-the-counter derivatives through central counterparties (CCPs). This regulatory change has radically reshaped the interconnected structure among counterparties and in turn has cast CCPs as systemically important financial institutions. While this regulatory reform is intended to mitigate counterparty risk and contagion, its equilibrium effect on financial resilience remains unclear. Our study adds value by analyzing a regulatory change to a historical banking system that is structurally similar to the effect of mandatory central clearing.

Our paper contributes to several literatures. First, our paper fits into the broad literature on banking regulations. While this literature is extensive (see Berger, Molyneux, and Wilson 2014 for a review), there is little discussion about the effects of banking regulations on networks. One exception is that of Erol and Ordoñez (2017), who model banks’ strategic formation of linkages in reaction to changes in liquidity requirements. We make empirical contributions to this literature by analyzing how reserve requirements affected banking networks and systemic risk during the National Banking era.

Second, we contribute to the theoretical literature on financial networks. Pioneered by Allen and Gale (2000) and Eisenberg and Noe (2001), an extensive theory literature studies contagion and systemic risk in financial networks.<sup>3</sup> In particular, Eisenberg and Noe (2001) develop a framework in which banks have interconnected liability relationships. This clearing framework is the ideal tool for assessing default cascades. We contribute to this literature by adding contagious withdrawals to the Eisenberg and Noe (2001) payment framework. This new feature allows us to study the propagation of funding risk due to sudden withdrawals of deposits.

Third, our study adds to the empirical and quantitative studies on financial network and stability (e.g., Furfine 2003; Nier et al. 2007; Gai and Kapadia 2010; Gai, Haldane, and Kapadia 2011; Glasserman and Young 2015). However, due to

<sup>3</sup> Some studies take the network structures as given, e.g., Dasgupta (2004); Gai, Haldane, and Kapadia (2011); Caballero and Simsek (2013); Elliott, Golub, and Jackson (2014); Greenwood, Landier, and Thesmar (2015); and Acemoglu, Ozdaglar, and Tahbaz-Salehi (2015), while others incorporate banks’ strategic responses in forming linkages, e.g., Leitner (2005); Acemoglu, Ozdaglar, and Tahbaz-Salehi (2014); Farboodi (2014); Wang (2015); Tran, Vuong, and Zeckhauser (2016); Erol and Vohra (2017); and Erol and Ordoñez (2017).

difficulties in identifying exact linkages and exposures among institutions, most studies are based on simulated networks rather than empirical networks. Also, some empirical studies examine how historical bank networks transmitted panics (e.g., Richardson 2007; Carlson, Mitchener, and Richardson 2011; James, McAndrews, and Weiman 2013). Nonetheless, the arguments are limited to the extent that exact bilateral risk exposures are not readily observable in the banking system. More recent studies use regulatory data to obtain information on the magnitude of exposures among banks. For instance, Calomiris and Carlson (2017) use detailed information on interbank networks to study the transmission of liquidity risks during the panic of 1893.<sup>4</sup> In addition, Anderson and Bluedorn (2017) use state banking reports to study Pennsylvania state banks' responses during the panic of 1884.<sup>5</sup> We fill this gap by using empirically observed interbank deposit relationships to construct bank networks before and after the NBAs.

Lastly, our paper contributes to the literature on banking panics during the National Banking era by empirically examining how the pyramiding of bank reserves would have contributed to systemic liquidity crises. While several studies have recognized the interbank network as a major source of systemic risk during this time, they do not provide empirical evidence or quantitative analysis (e.g., Calomiris and Gorton 1991; Sprague 1910; Kemmerer 1910; Gorton and Tallman 2016; Wicker 2006). Moreover, none of these studies compare the structure of the interbank network before and after the NBAs or assess how different networks affected financial panics. We contribute by providing empirical evidence using micro-level data.

This paper proceeds as follows. Section I provides historical background on the National Banking Acts and the correspondent banking system. Section II presents data and summary statistics. Section III describes the model, Section IV calibrates the model and discusses the quantitative results, and Section V concludes.

## I. Historical Background

The provisions of the National Banking Acts (NBAs) represented a major event in the development of the banking and financial infrastructure of the United States. The NBAs were passed with the intention to create a demand for US Treasury bonds during the Civil War because, without an income tax, they were the only way to finance the North's war effort. The NBAs created a system of national banks and encouraged state banks to convert. This new class of banks was allowed to issue bank notes worth up to 90 percent of the lower of par or the market value of the US Treasury securities they held. Because national bank notes were collateralized by US Treasury bonds and traded at par, a uniform national currency was created.<sup>6</sup> In

<sup>4</sup>Calomiris and Carlson (2017) use national banks' examination reports to obtain detailed information on interbank networks. This study differs from theirs in three aspects. First, while they study the panic of 1893, we focus on the passage of the NBAs and its effect on the banking system. Second, while they look at national banks, we study both state and national banks. Third, they use reduced-form regressions to examine shocks from New York City; we adopt a structural approach to analyze the equilibrium effects of two types of shocks, those originating from New York City and those coming from rural banks.

<sup>5</sup>Anderson and Bluedorn (2017) do not include national banks in their study. Their empirical analysis is similar to that of Calomiris and Carlson (2017).

<sup>6</sup>Prior to the NBAs, banks issued private bank notes that traded at discounts from face value when transactions took place at a distance from the issuing bank (Gorton 1999).

addition, the NBAs established a set of capital and reserve regulations that transformed the interbank network relationships.

### A. Reserve Hierarchy under the National Banking Acts

Interbank networks developed in the early 1800s when advances in transportation and communication technologies led to rapid growth in interregional trade and increased the need for interregional capital transfer within the United States. However, banks could not accommodate interregional payments easily because most banks operated as unit banks under legal restrictions on branching. Interbank network relationships were an institutional response to circumvent branching restrictions. Small rural banks kept deposits with larger city banks, which cleared their checks through city clearinghouses. We refer to banks placing deposits in other banks as *respondents* and banks providing the services as *correspondents*.<sup>7</sup>

Before the passage of the NBAs, the adoption of reserve requirements was handled solely by state regulators. Reserve requirements were first implemented by the states of Virginia, Georgia, and New York following the panic of 1837. Although other states also introduced reserve requirements in subsequent years, only 10 out of 33 states had such laws by the 1860s (Carlson 2015). The state of Pennsylvania did not have legal reserve requirements.<sup>8</sup>

One of the most important regulations under the NBAs, and the focal event of this paper was the creation of a reserve hierarchy (see Table 1). The top tier consisted of *central reserve city banks*. They were located in New York City when the NBAs were passed.<sup>9</sup> Central reserve city banks were required to hold reserves of at least 25 percent in lawful currency and notes, and they had to keep all their reserves in their vault. The middle tier comprised *reserve city banks*. They were located in Philadelphia and Pittsburgh for the state of Pennsylvania. The reserve city banks were also required to hold a 25 percent reserve. However, they were allowed to hold one-half of the 25 percent as correspondent deposits in a central reserve city bank and the rest in lawful currency. The bottom tier consisted of the remaining banks, which were called *country banks*. They were rural banks located outside the central reserve and reserve cities. They were required to hold a 15 percent reserve on deposits, with up to three-fifths of the 15 percent as correspondent deposits in central reserve or reserve city banks and the rest in cash.

This tiered system led to a concentration of correspondent balances in New York City and was considered a source of instability in the US banking system (Wicker 2006). Banks often held the maximum amount of reserves in reserve city and central reserve city banks to earn a 2 percent interest rate on the deposit accounts. The reserves tended to concentrate in New York City banks, which in turn lent sizably to investors to purchase stocks on margin (call loans).

<sup>7</sup>Correspondent banking offered other valuable services as well. Deposits placed in city correspondents provided rural banks an opportunity to invest in liquid assets that paid interest, thereby allowing them to diversify their asset portfolios. Also, these balances in major cities, especially New York, were traded among local banks outside financial centers. This helped the local banks adjust the level of correspondent accounts at lower transactions costs.

<sup>8</sup>See General Assembly of the State of Pennsylvania (1861) for bank regulatory requirements in Pennsylvania.

<sup>9</sup>Chicago and St. Louis became central reserve cities in 1887 (Carlson 2015).

TABLE 1—NATIONAL BANK RESERVE REQUIREMENTS

Tier	Banks	Location	Reserve ratio	Max reserve deposit	Cash in vault
1	Central reserve city banks	New York City	25 percent	0	1
2	Reserve city banks	Philadelphia, Pittsburgh	25 percent	1/2	1/2
3	Country banks	Others	15 percent	3/5	2/5

Source: Carlson (2015)

### B. Banking Panics of the National Banking Era

Under the National Banking system, the United States experienced a series of serious banking panics. These panics occurred as holders of bank liabilities demanded the conversion of their debt claims into cash *en masse* (Calomiris and Gorton 1991).<sup>10</sup> While the NBAs included other regulations as well, the reserve pyramiding was viewed as one of the major factors in magnifying the extent of banking crises during the periods of stress.

On the one hand, contemporaries considered the pyramiding of reserves and the interbank systems' inability to accommodate seasonal flows of funds between New York City and country banks to be sources of systemic risk, as shown in the National Monetary Commission reports (1910). In this view, banking crises originated at the bottom of the pyramid and spread to the top. This occurred as rural banks withdrew interbank balances from reserve city and central reserve city banks in times of "monetary stringency," causing a drain on the reserves at central reserve banks.<sup>11</sup> The withdrawal of funds by country banks resulted in financial strains on city correspondents, prompting a liquidity crisis among city banks and a suspension of cash payments in major cities. The panic of 1893 originated from country banks and spread to New York City banks.

On the other hand, unexpected financial shocks in New York City were also an important source of systemic liquidity crises.<sup>12</sup> New York City banks were systemically important for their size and interconnectedness. Financial shocks in New York City accompanied sharp spikes in the call money market rate and a curtailment in credit availability. Four out of five major panics occurred after an initial financial shock in New York City. In particular, the suspension of cash payments, which was carried out during the panics of 1873 and 1907, restricted depositors' access to their funds, prevented non-financial businesses from meeting payrolls, and created a currency premium.

The consensus among contemporaries has been that the pyramiding of reserves in New York City increased the vulnerability of the US banking system to banking

<sup>10</sup>There were five major financial panics during the National Banking era (Sprague 1910). During the three most severe crises (in 1873, 1893, and 1907), specie was hoarded and circulated at a premium over checks drawn on banks, which required the suspension of cash payment by the New York Clearinghouse (Carlson 2005). The panics of 1884 and 1890 were minor crises. During these panics, the New York City banks were able to contain financial shocks without suspending convertibility.

<sup>11</sup>Bank panics tended to occur in spring and fall. Country banks needed currency in spring because of costs related to the purchases of farming implements, and in late summer and early fall because of costs related to harvesting.

<sup>12</sup>These crises were triggered by failures of brokerage houses, such as the closing of Jay Cooke in 1873; Grant and Ward in 1884; Decker, Howell, and Co. in 1890; and Knickerbocker Trust Company in 1907.

crises because of unexpectedly large demands for currency arising from the countryside during harvest and planting seasons. Recently, however, this view has been challenged as scholars emphasize the importance of liquidity shocks from New York City (Wicker 2006). One possibility is that reserve and central reserve city banks accumulated cash reserves to offset liquidity demands in anticipation of shocks from the interior, but they could not implement preventive measures to counteract unanticipated shocks in New York City. In Section IV, we examine how the banking system would respond to these two types of liquidity shocks before and after the NBAs.

### *C. Reactions to Crises: New York Clearinghouse*

Clearinghouses provided mechanisms for coordinating banks' responses to panics. Originally organized to provide an efficient way to clear checks, these coalitions of banks evolved into much more. More specifically, in response to banking panics, they acted as lenders of last resort, providing temporary liquidity to their members. Under branch banking restrictions, clearinghouses and their cooperative benefits were limited to city-level coalitions. Among them, the New York Clearinghouse played a dominant role.

During banking panics, the New York Clearinghouse issued clearinghouse loan certificates as joint liabilities of the clearinghouse members. They accepted part of member banks' portfolios as collateral in exchange for clearinghouse loan certificates, thereby creating a market for the illiquid assets.<sup>13</sup> In the absence of a formal lender of last resort, these loan certificates provided temporary liquidity to the banking system.

When panics could not be contained by the issuance of loan certificates, clearinghouses suspended the convertibility of deposits into cash. Such suspensions of convertibility were intended to limit the drain of cash reserves from the banking system by preventing runs. All five major panics in the National Banking era required the circulation of clearinghouse loan certificates. Three of the five panics (in 1873, 1893, and 1907) required the suspensions of convertibility. In Section IVC, we study the role of these actions.

## **II. Data and Summary Statistics**

### *A. Data*

We use a combination of data sources to study how the introduction of the NBAs changed the structure of bank networks and affected the stability of the banking system. The first source is the *Reports of the Several Banks and Savings Institutions of Pennsylvania* (Auditor General of Pennsylvania 1863, 1868), which provide quarterly balance sheets for all state banks and savings institutions. The second source

<sup>13</sup> An individual clearinghouse member bank that needed loan certificates would have its loans and bonds examined by the clearinghouse loan committee to determine the quality of its collateral. Upon accepting it, the clearinghouse provided temporary loans up to 75 percent of the perceived collateral value. Banks with deficits could use loan certificates instead of regular currency to settle balances. If a deficit bank failed and the collateral was insufficient to cover the loan certificates, the clearinghouse members jointly shared the loss.



is the National Banks' Examination Reports, which were filed by the national bank examiners after their annual examinations.

Pennsylvania had a diverse economy with various types of banks (Weber 2003), which makes it an ideal state to study how the establishment of reserve requirements reshaped interbank networks and affected financial stability. Banks in rural agricultural areas, in the Southeast in particular, operated as unit banks and provided loans to local farmers. Banks in manufacturing areas around Pittsburgh served as correspondent banks for rural banks and issued industrial loans. And finally, banks in Philadelphia served as financial centers and lent to large industrial clients. Pennsylvania banks thus represent a heterogeneous set of correspondent relationships and therefore are a good starting point for understanding the US banking system overall.

From these reports, we collect information on balance sheets and correspondent relationships for state and national banks.<sup>14</sup> For state banks, we have information on the name of each correspondent and the amount that was due from each of them.<sup>15</sup> For national banks, we collect information on the amount that was due from each agent and the name of each agent. Although state banking reports provided complete information about correspondents, national banks' examination reports recorded relationships only between national banks and their approved reserve agents since these amounts would later be verified at the correspondent banks to ensure that each national bank met its reserve requirements. Online Appendix A1 provides further details on how we collect information for the state and national banks.

We study the years 1862 and 1867 to capture the structure of bank networks before and after the enactment of the NBAs. The data for 1862 are only from state banks and capture bank behavior before the unanticipated passage of the NBAs. In contrast, the data for 1867 contain both state and national banks and capture bank behavior after the passage of the NBAs. The year 1867 is selected for two reasons. First, in the absence of deposit insurance, finding reliable correspondent banks would have been time-consuming for both converted and newly established national banks. Second, national banks' examination reports do not provide information on national banks' reserve agents until 1867.<sup>16</sup>

We divide the sample of banks into four classes according to their location: New York City, Philadelphia, Pittsburgh, and country banks. As documented in Weber (2003), differences in the needs of the customers of each class of banks mostly originated from location, shaping how they interacted with each other. The NBAs designated New York City as the central reserve city and Philadelphia and Pittsburgh

<sup>14</sup>The interbank deposit information recorded for Pennsylvania state banks offers a unique opportunity to study interbank relationships. Most states do not report due-from information on bank balance sheets or only report the aggregate amount without any details on banks' counterparties. Other states, such as New York, report the name of the correspondent bank, but they do not report any information on the amount of deposits placed in this bank.

<sup>15</sup>A "due-to" account is a liability on a bank's balance sheet that indicates the amount of deposits payable to another bank. A "due-from" account is an asset on a bank's balance sheet that indicates the amount of deposits currently held at another bank.

<sup>16</sup>We have state bank balance sheets for the years 1862 and 1867 and national bank balance sheets for 1867. Due to differences in reported items between state bank balance sheets and national bank balance sheets, we create standardized asset and liability categories. The asset categories are cash; government securities; other securities; amounts due from other banks; loans; and other assets. The liability categories are capital; notes; deposits; amounts due to other banks; surplus; and other liabilities. Online Appendix A2 presents the method for balance sheet standardization.

TABLE 2—BALANCE SHEET SUMMARY STATISTICS

	New York City banks		Philadelphia banks		Pittsburgh banks		Country banks	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Year: 1862								
Against total assets	Observations: 22		Observations: 20		Observations: 7		Observations: 64	
Cash	0.19	0.09	0.21	0.10	0.18	0.06	0.11	0.07
Securities	0.16	0.14	0.30	0.14	0.32	0.13	0.18	0.14
Due from other banks	0.04	0.02	0.03	0.04	0.12	0.04	0.18	0.10
Loans	0.58	0.17	0.40	0.12	0.36	0.12	0.50	0.13
Against total liabilities								
Equity	0.35	0.07	0.24	0.06	0.36	0.07	0.28	0.09
Bank notes	0.04	0.03	0.13	0.10	0.39	0.17	0.40	0.22
Deposits	0.43	0.13	0.51	0.09	0.23	0.12	0.28	0.20
Due to other banks	0.13	0.11	0.09	0.09	0.01	0.01	0.01	0.02
Year = 1867								
Against total assets	Observations: 19		Observations: 28		Observations: 19		Observations: 132	
Cash	0.38	0.15	0.25	0.07	0.11	0.06	0.10	0.04
Securities	0.18	0.13	0.26	0.13	0.33	0.10	0.37	0.14
Due from other banks	0.04	0.04	0.05	0.04	0.06	0.03	0.10	0.07
Loans	0.39	0.13	0.40	0.09	0.47	0.08	0.40	0.13
Against total liabilities								
Equity	0.25	0.11	0.29	0.08	0.39	0.13	0.38	0.10
Bank notes	0.09	0.05	0.15	0.07	0.23	0.10	0.26	0.10
Deposits	0.46	0.17	0.49	0.12	0.35	0.20	0.33	0.16
Due to other banks	0.19	0.17	0.06	0.08	0.03	0.03	0.03	0.03

Notes: Equity is the sum of capital and surplus. Securities is the sum of government securities and other securities. The balance sheet fractions are computed against individual banks' total asset values or liability values.

as reserve cities. Depending on their location, banks faced different regulations, which were reflected in their balance sheets. Specifically, New York City banks were big and served as depositories for other banks. Country banks were generally small and served as creditors to banks in major financial centers. Both Philadelphia and Pittsburgh banks served as intermediaries for other banks by taking deposits from country banks and placing them in New York City banks. However, some Philadelphia banks behaved more like central reserve city banks by maintaining large cash reserves and serving as ultimate depository institutions. Pittsburgh banks instead behaved more like country banks by acting as creditor banks to financial center banks.

### B. Balance Sheet Information

The average bank held similar levels of cash and interbank deposits before and after the rule change. Before the NBAs, banks held 15 percent of cash, 19 percent of securities, and 12 percent of interbank deposits. After the NBAs, banks held 15 percent of cash, 33 percent of securities, and 8 percent of interbank deposits. Overall, banks had a liquid balance sheet structure.

The balance sheet structure differed among banks based on their locations and business types. Table 2 shows the composition of balance sheets for New York City, Philadelphia, Pittsburgh, and country banks in 1862 and 1867. Notably, banks that

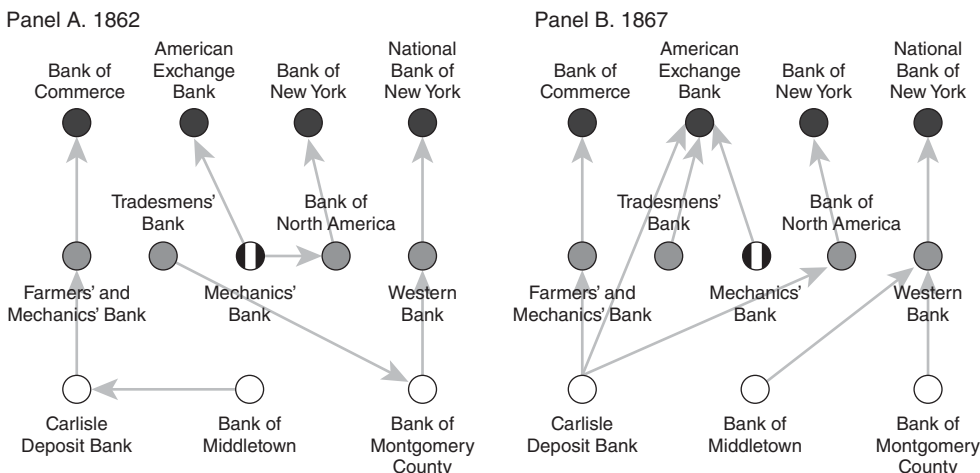


FIGURE 1. A 12-BANK EXAMPLE NETWORK

Notes: This figure shows the interbank correspondent relationships among 12 banks in 1862 and 1867. The nodes colored in black, gray, black with a white stripe, and white indicate New York City banks, Philadelphia banks, Pittsburgh banks, and country banks, respectively. The bank nodes are ordered in a three-layer hierarchy, from top to bottom following the NBAs reserve pyramid, with the central reserve city banks in the top row, reserve city banks in the middle row, and non-reserve cities in the bottom row. A link with an arrow indicates a recorded deposit relationship in which the arrow points to the correspondent.

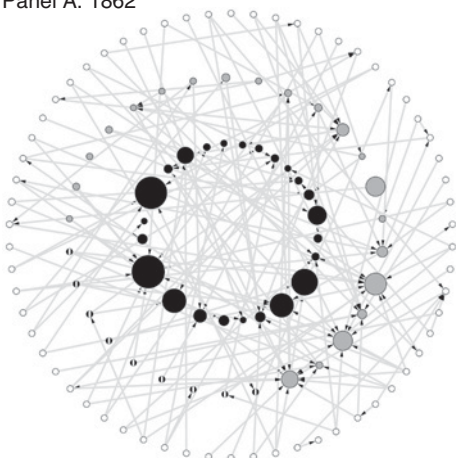
served as depositories for country banks increased their cash holdings after the NBAs. New York City banks increased cash holdings significantly from 19 percent in 1862 to 38 percent in 1867. While higher cash holdings were required under the newly established reserve requirements, these banks were holding more than the amount needed. Banks in Philadelphia, which also served as bankers' banks at the time, increased cash holdings as well. In contrast, Pittsburgh banks, which were not as important as financial center banks compared to those in Philadelphia, actually decreased cash holdings. The level of their cash holdings was close to that of country banks. Beyond these observations, the liabilities structures of banks were quite comparable, before and after.

C. Interbank Network

The reserve requirements of the NBAs reshaped the interbank network by shifting the destination of interbank deposits. A reserve pyramid with three distinct tiers emerged. We observe that interbank relationships became clustered in cities that were designated as the reserve and central reserve cities. Furthermore, a few New York City banks turned into the dominant repository of interbank deposits.

To fix ideas, let us look at how the correspondent relationships changed in an example of 12 banks; see Figure 1. This example network includes four New York City banks (colored in black), four Philadelphia banks (colored in gray), one Pittsburgh bank (colored in black with a white stripe), and three country banks (colored in white). In 1862, each New York City bank had only one respondent; country banks such as Carlisle Deposit Bank and the Bank of Montgomery County both received interbank deposits. After the NBAs were enforced, banks changed their connections

Panel A. 1862



Panel B. 1867

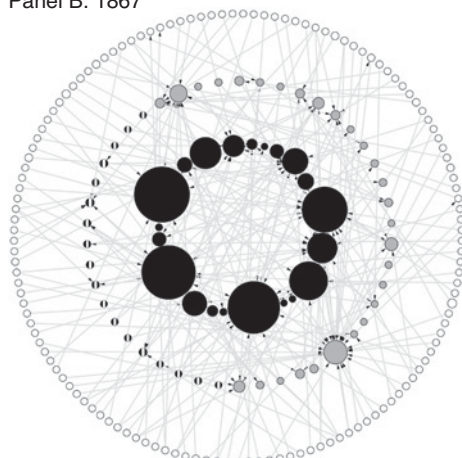


FIGURE 2. INTERBANK NETWORK

*Notes:* This figure depicts interbank networks in 1862 and 1867. The nodes colored in black, gray, black with a white stripe, and white indicate New York City banks, Philadelphia banks, Pittsburgh banks, and country banks, respectively. The nodes are laid out along three concentric rings based on the NBAs reserve hierarchy, with banks located at the central reserve city organized along the center ring, the reserve city banks along the mid-sized ring, and non-reserve city/country banks along the outer ring. The diameter of each node is proportional to the bank's log size of interbank deposits received on the liability side of the balance sheet. A link with an arrow indicates a recorded deposit relationship in which the arrow points to the correspondent.

to align with the reserve requirements. For instance, the Bank of Middletown terminated its relationship with the Carlisle Deposit Bank and formed a new relationship with the Western Bank, a bank in Philadelphia. In addition, the Tradesmens' Bank, located in a reserve city of Philadelphia, established a relationship with a New York City bank by changing its correspondent from the Bank of Montgomery County to the American Exchange Bank. Finally, a Pittsburgh bank, the Mechanics' Bank, no longer maintained its relationship with the Bank of North America in Philadelphia. A direct consequence of these observed relationship changes was a concentration of interbank deposits at the American Exchange Bank in New York City. These observed changes are typical examples of what happened in response to the NBAs' rule change.

To examine the consequences of the NBAs in aggregate, we first analyze data on due-to deposits on the liability side of banks' balance sheets. Figure 2 visualizes the concentration of interbank deposits towards central reserve city banks. The two networks present the directional flows of interbank deposits before and after the NBAs. A node indicates a bank and a link with an arrow indicates a recorded deposit relationship with the arrow pointing to the correspondent. The nodes are laid out along three concentric rings according to the banks' locations in the reserve hierarchy; the inner ring represents banks in the central reserve city, the middle ring represents those in reserve cities, and the outer ring represents those in rural areas

(also referred to as country banks). Each node is sized by the bank's total interbank deposits received on the liability side of its balance sheet, thus reflecting its significance in the correspondent markets.

Figure 2 shows that the NBAs accelerated a concentration of interbank linkages among banks in designated reserve and central reserve cities. Notably, the NBAs consolidated New York's position as the nation's financial center. Before the NBAs, the size of interbank due-to deposits received by the largest banks in New York City and Philadelphia was comparable, suggesting that both cities were equally important financial centers. After the NBAs, the size of interbank, due-to deposits received by the largest New York City banks, was ten times larger than that of Philadelphia banks, indicating that New York City banks had become the ultimate reserve depositories.

As the NBAs took root, another notable change was the influx of new banks, especially outside financial centers. The number of banks in Pennsylvania and New York City increased from 113 in 1862 to 198 in 1867. This was primarily driven by a doubling of country banks from 64 to 132. While bank entries could have partially contributed to the observed deposits concentration, we confirm that the documented network changes came from the regulation and were not simply a consequence of bank entries. In online Appendix B, we examine the distribution of interbank deposits across converted national, new national, and state banks. Evidence shows that the same level and structure of concentration would not have appeared without the rule change by the NBAs, and therefore, was not a mere reflection of the increased volume of the banking sector.

Similar patterns of deposits concentration are visible when we focus on the micro-level linkage data, recorded as the due-from deposits of Pennsylvania banks on the asset side of the balance sheets. Table 3 shows the distribution of correspondent deposits for the years 1862 and 1867 grouped by the origin and destination of interbank deposits. The columns show the locations of respondent banks and the rows show the locations of correspondent banks. For a given location of respondent banks, the columns provide the percentages of due-from deposits and correspondent relationships going to different correspondent locations. The percentages of each column sum up to 1.

Both the deposit size and the correspondent relationships highlight the increasing importance of New York City as the destination of deposits relative to Philadelphia, confirming the earlier findings using due-to deposits. Philadelphia and Pittsburgh banks shifted a larger portion of their deposits to New York City rather than keeping them locally. For example, Philadelphia banks placed 75.6 percent of interbank deposits and 38.1 percent of correspondent relationships at New York City in 1862; both values became 100 percent in 1867 and the deposits going elsewhere reduced to zero.<sup>17</sup> Additionally, there was a shift in deposits to Pittsburgh by country banks during this period. This trend suggests that Pittsburgh banks began to function as a major correspondent city as a result of the NBAs, though the amounts of interbank deposits were smaller than those in Philadelphia and New York City.

<sup>17</sup>One piece of micro-level evidence for this change is the discontinued relationship between the Tradesmen's Bank of Philadelphia and the Bank of Montgomery County in the example shown in Figure 1.

TABLE 3—DISTRIBUTION OF INTERBANK DEPOSITS

	All banks		Philadelphia banks		Pittsburgh banks		Country banks	
	Amount	Links	Amount	Links	Amount	Links	Amount	Links
Year: 1862								
New York City	45.9	36.4	75.6	38.1	79.2	57.1	31.8	33.0
Philadelphia	50.7	41.4	13.5	11.9	16.6	28.6	66.3	54.7
Pittsburgh	0.4	1.2	0.0	0.0	0.0	0.0	0.5	1.9
Other PA	2.2	13.0	5.9	23.8	3.1	7.1	1.4	9.4
Other US	0.8	8.0	5.0	26.2	1.1	7.1	0.0	0.9
Year: 1867								
New York City	62.2	46.2	100.0	100.0	90.1	82.6	30.8	31.3
Philadelphia	32.0	41.5	0.0	0.0	7.8	13.0	58.8	53.1
Pittsburgh	4.3	7.5	0.0	0.0	2.1	4.3	7.5	9.4
Other PA	0.5	1.9	0.0	0.0	0.0	0.0	0.9	2.5
Other US	1.0	2.8	0.0	0.0	0.0	0.0	2.0	3.8

*Notes:* This table shows the distribution of correspondent deposits of Pennsylvania banks for the years 1862 and 1867. All numbers are in percentages. The rows indicate the location of correspondent banks. The columns indicate the location of respondent banks. We classify respondent banks into three groups: Philadelphia banks, Pittsburgh banks, and country banks. The columns show the fractions of deposits held at different locations against total major due-from deposits in all respondents, those in Philadelphia, in Pittsburgh, and in country banks.

### III. Model

Understanding interbank contagion requires an equilibrium model. To this end, we develop a model that extends the existing interbank clearing framework (e.g., Eisenberg and Noe 2001; Acemoglu, Ozdaglar, and Tahbaz-Salehi 2015) by allowing for endogenous deposit withdrawals. This new feature allows for a novel contagion mechanism which is critical for banking crises. In the model, banks issue demand deposits and invest in long-term loans, so they are subject to liquidity risk. Their interbank liability relationships establish the network linkages. Taking the linkages as given, banks can withdraw deposits from and default on other banks: this is how contagion occurs. We solve for the payment equilibrium and quantify the interbank contagion.

#### A. Environment

There are  $N$  banks,  $i = \{1, 2, \dots, N\}$ . Each bank has a representative local retail depositor. The economy has three dates ( $t = 0, 1, 2$ ) and there is no discounting.

At  $t = 0$ , bank  $i$  is endowed with equity capital, deposits from its representative retail depositor, and interbank deposits due to other bank depositors. Let  $K_i > 0$  denote its equity capital. Let  $\mathbf{D}$  denote the exogenously given deposit matrix:<sup>18</sup>  $D_{ii} > 0$  is bank  $i$ 's deposit from its retail depositor; the off-diagonal element  $D_{ij} \geq 0$  is the interbank deposit at bank  $j$  due to bank  $i$ , here bank  $i$  is the depositor or

<sup>18</sup>The weighted interbank liability relationships are exogenously given at  $t = 0$ . We do not model the endogenous formation of linkages, as the goal here is not to understand why the network changed the way it did after the NBAs, but rather to take the changes as given and analyze how they would have affected the transmission of shocks and the vulnerability of the system.

TABLE 4—BALANCE SHEET OF BANK  $i$  AT  $t = 0$

Assets	Liabilities and equity
Vault cash $C_i$	Equity capital $K_i$
Investment in loans and securities $I_i$	Retail deposits and banknotes $D_{ii}$
Deposits due from other banks $\sum_{j \neq i} D_{ij}$	Deposits due to other banks $\sum_{j \neq i} D_{ji}$

respondent, bank  $j$  is the debtor or correspondent. The total deposits at bank  $i$  amount to  $\sum_j D_{ji}$ . They are in the form of demand deposits with a maturity of two periods but can be withdrawn early at  $t = 1$ . The total assets of bank  $i$  include vault cash  $C_i > 0$ , investment in loans and securities  $I_i > 0$ , and interbank deposits due from other banks  $\sum_{j \neq i} D_{ij}$ . The balance sheet items at the initial date are summarized in Table 4.

A bank’s investment in loans and securities is long term. It matures at the final date  $t = 2$  with return rate  $R_i^2$  so that the proceeds from investment amount to  $I_i R_i^2$  if held to maturity. The investment is risky: the return rate  $R_i^2$  satisfies

$$(1) \quad R_i^1 = R_i^0 + \varepsilon_i^1, \quad R_i^2 = R_i^1 + \varepsilon_i^2,$$

where  $R_i^0$  and  $R_i^1$  are the expected rates of return at  $t = 0, 1$ , respectively, and  $\varepsilon_i^t$  are shocks. The shocks  $\varepsilon^t$  are drawn from zero mean multivariate normal distributions with a covariance matrix  $\Sigma$ . The investment returns are correlated among banks to reflect correlated asset investments.

### B. Interbank Clearing

Banking crises during the National Banking era were episodes of elevated redemption requests. Massive withdrawals by retail depositors and respondent banks created liquidity shortages at city correspondents, resulting in costly liquidations and defaults. The ultimate liquidation risk of banks is tied to whether they could successfully redeem the interbank deposits held at their correspondents.

To quantify such contagion effect, we extend the Eisenberg and Noe (2001) clearing system to a two-period setting with liquidity withdrawals. Let matrices  $\mathbf{W}^t$  denote depositors’ withdrawal decisions at  $t = 1, 2$ :  $W_{ii}^t$  takes the value 1 if at time  $t$  the representative retail depositor withdraws all deposits from bank  $i$  and 0 otherwise;  $W_{ij}^t$  takes the value 1 if at time  $t$  bank  $i$  withdraws all interbank deposits held at bank  $j$  and 0 otherwise. In particular,  $\mathbf{W}^1$  reflects the *liquidity withdrawals* before maturity. Since deposits mature in two periods,  $W_{ij}^2 = 1 - W_{ij}^1$  holds by definition.<sup>19</sup> Let matrix  $\mathbf{X}^t$  denote the clearing payments:  $X_{ii}^t$  is the payment by bank  $i$  upon its retail depositor’s withdrawal at time  $t$  and  $X_{ji}^t$  is the payment by bank  $i$  upon a respondent bank  $j$ ’s withdrawal at time  $t$ .

At  $t = 1$ , the liquidation needs of a bank depend on how the amount of liquidity withdrawal requests compares with its liquid assets. Bank  $i$ ’s liquid assets at  $t = 1$

<sup>19</sup>The total withdrawal demands bank  $i$  faces at time  $t$  is  $\sum_j W_{ji}^t D_{ji}$ . The final date withdrawals  $\sum_j W_{ji}^2 D_{ji} = \sum_j (1 - W_{ji}^1) D_{ji}$  are predetermined at  $t = 1$ .

include vault cash  $C_i$  and the interbank deposits redeemed  $\sum_{j \neq i} X_{ij}^1$ . If the liquid assets of bank  $i$  fail to meet its liquidity withdrawal requests even after the bank has withdrawn all deposits due from correspondents, bank  $i$  has to go through a costly *liquidation* of the long-term investment.<sup>20</sup> Denote  $\mathbf{1}_i^l$  the indicator variable that takes the value 1 if a liquidation event happens at bank  $i$  and 0 otherwise, i.e.,

$$(2) \quad \mathbf{1}_i^l = \begin{cases} 1 & \text{if } C_i + \sum_{j \neq i} X_{ij}^1 - \sum_j W_{ji}^1 D_{ji} < 0 \text{ and } \sum_{j \neq i} W_{ij}^1 D_{ij} = \sum_{j \neq i} D_{ij}. \\ 0 & \text{otherwise} \end{cases}$$

In a liquidation event, bank  $i$  liquidates the entire investment at a cost, yielding  $\xi I_i$ ,  $\xi < 1$ . The salvage value comes at a cost caused, for example, by the sale of loans at a discount. The liquidation costs imply that bank runs have real economic consequences as banks recall loans and terminate productive investments.

Let  $A_i^t$  denote bank  $i$ 's *total available assets* at time  $t$ . If the total available assets exceed bank  $i$ 's withdrawal requests by depositors, bank  $i$  fulfills the withdrawal requests in full and keeps the remaining assets; otherwise, bank  $i$  defaults at time  $t$ . Denote  $\mathbf{1}_i^{dt}$  the indicator variable that takes the value 1 if bank  $i$  defaults at time  $t$  and 0 otherwise, i.e.,

$$(3) \quad \mathbf{1}_i^{dt} = \begin{cases} 1 & \text{if } A_i^t - \sum_j W_{ji}^t D_{ji} < 0. \\ 0 & \text{otherwise} \end{cases}$$

We proceed to define the total available assets,  $A_i^t$ . Accounting for potential liquidation at the intermediate date,  $A_i^1$  equals the sum of vault cash, interbank deposits redeemed from correspondents, and the liquidation yields, i.e.,

$$(4) \quad A_i^1 = C_i + \sum_{j \neq i} X_{ij}^1 + \mathbf{1}_i^l \xi I_i.$$

If bank  $i$  defaults at  $t = 1$ , it is removed from the final date clearing system, so  $A_i^2 = 0$ ; if the bank survives at  $t = 1$ , the available assets  $A_i^2$  include the remaining assets net of withdrawals from  $t = 1$ , matured payments by correspondents at  $t = 2$ , and the realized investment proceeds if held to maturity. Formally,

$$(5) \quad A_i^2 = (1 - \mathbf{1}_i^{d1}) \left( A_i^1 - \sum_j W_{ji}^1 D_{ji} + \sum_{j \neq i} X_{ij}^2 + (1 - \mathbf{1}_i^l) I_i R_i^2 \right).$$

A defaulting bank pays all depositors on a *pro rata* basis, resulting in zero equity value. While retail depositors have seniority in payment today, retail depositors and

<sup>20</sup>We implicitly assume that when they face liquidity shortages, banks would first use all available liquid assets (cash and due-from deposits) before invoking a costly liquidation. Gorton and Tallman (2018) provide evidence that banks scrambled for cash reserves (or substitutes) to support their loans and investments during National Banking era panics. While less frequent, liquidation occurred during a typical bank panic; as discussed by Miron (1986), in the absence of a lender of last resort, a bank would be forced to call in loans to meet deposit demand following a large deposit withdrawal.



respondent banks had the same seniority during the National Banking era. The payment by bank  $i$  to its depositor  $k$  at time  $t = 1, 2$  is given by

$$(6) \quad X_{ki}^1 = \frac{W_{ki}^1 D_{ki}}{\sum_j W_{ji}^1 D_{ji}} \min \left\{ \sum_j W_{ji}^1 D_{ji}, A_i^1 \right\},$$

$$X_{ki}^2 = \frac{(1 - \mathbf{1}_k^{d1}) W_{ki}^2 D_{ki}}{\sum_j W_{ji}^2 D_{ji}} \min \left\{ \sum_j W_{ji}^2 D_{ji}, A_i^2 \right\}.$$

### C. Depositors' Withdrawal Decisions

The respondent banks and the representative retail depositors make withdrawal decisions at  $t = 1$ . Since we do not explicitly model the interest rate, we assume that depositors only withdraw when doing so is a strictly dominant strategy.

Respondent banks are risk-neutral and have full information about bank fundamentals (balance sheets and expected returns) and equilibrium outcomes. A respondent bank  $i$  optimally chooses to withdraw early from correspondents to avoid default and to maximize its expected profits,  $E_1 \left[ \left( A_i^2 - (1 - \mathbf{1}_i^{d1}) \sum_j W_{ji}^2 D_{ji} \right)^+ \right]$ , where  $(\cdot)^+$  stands for  $\max\{\cdot, 0\}$ , and  $E_1[\cdot]$  stands for expectation taken at  $t = 1$ . Plugging in equations (4)–(5), we obtain that the respondent bank  $i$ 's problem is equivalent to<sup>21</sup>

$$(7) \quad \max_{\{W_{ij}^l \in \{0,1\}\}_{j \neq i}} (1 - \mathbf{1}_i^{d1}) E_1 \left[ \left( \sum_{j \neq i} (X_{ij}^1 + X_{ij}^2) - \mathbf{1}_i^l (R_i^2 - \xi) I_i + C_i + I_i R_i^2 - \sum_j D_{ji} \right)^+ \right].$$

Hence, a bank aims to avoid an early default and, if that is successful, to maximize total deposit redemptions. In solving problem (7), the withdrawal decisions satisfy the following conditions.

First, to avoid an early default, a bank withdraws its interbank deposits in response to its own liquidity needs. From equations (2)–(4), if the liquid assets cannot meet its liquidity withdrawal requests, bank  $i$  withdraws all its deposits due from correspondent banks,<sup>22</sup> i.e.,

$$(8) \quad C_i + \sum_{j \neq i} X_{ij}^1 - \sum_j W_{ji}^1 D_{ji} < 0 \Rightarrow \sum_{j \neq i} W_{ij}^1 D_{ij} = \sum_{j \neq i} D_{ij}.$$

Second, to maximize deposit redemptions, a respondent bank withdraws if the correspondent bank  $i$  defaults early or is expected to default at  $t = 2$ . The condition further depends on whether bank  $i$  liquidates the investment. In the case of  $\mathbf{1}_i^l = 1$ ,

<sup>21</sup>The expected profits equal  $E_1 \left[ \left( (1 - \mathbf{1}_i^{d1}) (A_i^1 - \sum_j W_{ji}^1 D_{ji} + \sum_{j \neq i} X_{ij}^2 + (1 - \mathbf{1}_i^l) I_i R_i^2 - \sum_j W_{ji}^2 D_{ji}) \right)^+ \right]$ . Since  $(1 - \mathbf{1}_i^{d1}) \geq 0$  and  $\mathbf{1}_i^{d1}$  is a deterministic outcome at  $t = 1$ , we can take it out of  $E_1[\cdot]$ . Rearranging the terms gives (7).

<sup>22</sup>While in principle a bank could withdraw partially to satisfy its exact liquidity needs, here for simplicity we assume that a bank under liquidity needs withdraws all its deposits due from correspondents. To show condition (8), suppose for contradiction that  $C_i + \sum_{j \neq i} X_{ij}^1 - \sum_j W_{ji}^1 D_{ji} < 0$  and  $\sum_{j \neq i} W_{ij}^1 D_{ij} < \sum_{j \neq i} D_{ij}$ . Then from (2), liquidation is not triggered and the bank would default at  $t = 1$ . Hence, a bank would withdraw all interbank deposits to avoid an early default.

there are no further cash flows arriving, following from equation (2), as bank  $i$  will have withdrawn all deposits due from correspondents at  $t = 1$ ; hence, bank  $i$  defaults at either date if and only if the available assets fall short of total liabilities, i.e.,  $A_i^1 < \sum_j D_{ji}$ . In the case of  $\mathbf{1}_i^1 = 0$ , the investment yield is stochastic; hence, bank  $i$  is expected to default at  $t = 2$ , i.e.,  $E_1[\mathbf{1}_i^{d2} | \mathbf{1}_i^1 = 0] = 1$ , when it has a low-enough expected return  $R_i^1$ . Formally, for any respondent bank  $k$  of bank  $i$ ,<sup>23</sup>

$$(9) \quad (\mathbf{1}_i^1 = 1) \wedge \left( A_i^1 - \sum_j D_{ji} < 0 \right) \Rightarrow W_{ki}^1 = 1;$$

$$(10) \quad (\mathbf{1}_i^1 = 0) \wedge \left( A_i^1 + \sum_{j \neq i} E_1[X_{ij}^2] + I_i R_i^1 - \sum_j D_{ji} < 0 \right) \Rightarrow W_{ki}^1 = 1,$$

where  $\wedge$  denotes the conjunction of the two statements.

Unlike the respondent banks, retail depositors lack information about fundamentals and equilibrium outcomes.<sup>24</sup> They make withdrawal decisions facing uncertainty about bank solvency. To capture this notion, we assume that the retail depositor has Knightian uncertainty (1921).<sup>25</sup> Following Caballero and Krishnamurthy (2008) and Caballero and Simsek (2013), we adopt a Maxmin expected utility representation and write the problem of the retail depositor at bank  $i$  as

$$\max_{w_{ii}^1 \in \{0,1\}} \min_{\tilde{\mathbf{1}}_i^{d1} \in \Theta_i} E_1 \left[ (X_{ii}^1 + X_{ii}^2) | \tilde{\mathbf{1}}_i^{d1} \right],$$

where  $\tilde{\mathbf{1}}_i^{d1}$  denotes the perceived default outcome of bank  $i$  at  $t = 1$  by its retail depositor, and  $\Theta_i$  denotes the set of perceived possible outcomes of  $\tilde{\mathbf{1}}_i^{d1}$  subject to the retail depositor’s information set, such that  $\tilde{\mathbf{1}}_i^{d1} \in \Theta_i$ . The operator  $\min_{\tilde{\mathbf{1}}_i^{d1} \in \Theta_i}$  evaluates all the perceived possible outcomes of  $\tilde{\mathbf{1}}_i^{d1}$  and selects the worst-case scenario.

The retail depositor is assumed to be generally uninformed about the environment except for the occurrence of two events, which identifies the set of perceived possible outcomes,  $\Theta_i$ . A retail depositor knows about the withdrawal requests at her bank, i.e.,  $\sum_{j \neq i} W_{ji}^1 D_{ji} > 0$ , for instance by watching queues lining up outside her bank. She also knows about the defaults of her bank’s correspondents (equivalently, her bank failing to redeem its due-froms in full), i.e.,  $\sum_{j \neq i} (X_{ij}^1 - W_{ij}^1 D_{ij}) < 0$ , for instance

<sup>23</sup>To derive condition (9), note that the liquidating bank  $i$  withdraws all deposits due from correspondents so  $\sum_{j \neq i} X_{ij}^2 = 0$ . Hence,  $\mathbf{1}_i^{d1} = 1$  if and only if  $A_i^1 < \sum_j W_{ji}^1 D_{ji}$ ; and  $\mathbf{1}_i^{d2} = 1$  if and only if  $\sum_j W_{ji}^1 D_{ji} \leq A_i^1 < \sum_j D_{ji}$ . Combining the two scenarios, we obtain that  $\mathbf{1}_i^{d1} + \mathbf{1}_i^{d2} = 1$  if and only if  $A_i^1 < \sum_j D_{ji}$ . To derive condition (10), note that  $\mathbf{1}_i^1 = 0$  implies that  $\mathbf{1}_i^{d1} = 0$  and  $A_i^2 = A_i^1 - \sum_j W_{ji}^1 D_{ji} + \sum_{j \neq i} X_{ij}^2 + I_i R_i^2$ . Hence,  $E_1[\mathbf{1}_i^{d2} | \mathbf{1}_i^1 = 0] = 1$  if and only if  $E_1[A_i^2 | \mathbf{1}_i^1 = 0] < \sum_j W_{ji}^2 D_{ji}$ , which is equivalent to  $A_i^1 + \sum_{j \neq i} E_1[X_{ij}^2] + I_i R_i^1 < \sum_j D_{ji}$ .

<sup>24</sup>This is motivated by the fact that bank runs in the nineteenth century were rampant among depositors who worried about bank solvency. For historical evidence about the role of uninformed depositors on bank panics, see, e.g., Sprague (1910); Rolnick and Weber (1985); Carlson (2005); Ramirez and Zandbergen (2014); Frydman, Hilt, and Zhou (2015); Calomiris and Carlson (2017); and Gorton and Tallman (2018).

<sup>25</sup>Knightian uncertainty is considered a central ingredient in banking crises. Greenspan (2004, p. 7) comments: “When confronted with uncertainty, especially Knightian uncertainty, human beings invariably attempt to disengage from medium to long-term commitments in favor of safety and liquidity.” Caballero and Krishnamurthy (2008) formalize a model in which institutions have Knightian uncertainty over liquidity need and analyze the role of government liquidity assistance. Caballero and Simsek (2013) demonstrate how fire sales can arise when banks face Knightian uncertainty about the network of cross exposures. The application of Knightian uncertainty coupled with condition (11) is a reduced-form modeling of how uninformed depositors withdraw based on adverse information about their banks, but it is both realistic to conceptualize the patterns in the historical panic runs and technically convenient.

from newspaper reports.<sup>26</sup> The occurrence of any of these events signals an adverse situation at the bank and makes the retail depositor perceive that the bank could default in equilibrium. Formally, if  $\sum_{j \neq i} W_{ji}^1 D_{ji} > 0$  or  $\sum_{j \neq i} (X_{ij}^1 - W_{ij}^1 D_{ij}) < 0$ , then  $\mathbf{1}_i^{d1} \in \{0, 1\}$ ; otherwise,  $\mathbf{1}_i^{d1} = 0$ , i.e.,

$$(11) \quad \Theta_i = \begin{cases} \{0, 1\} & \text{if } \sum_{j \neq i} W_{ji}^1 D_{ji} > 0 \text{ or } \sum_{j \neq i} (X_{ij}^1 - W_{ij}^1 D_{ij}) < 0 \\ \{0\} & \text{otherwise} \end{cases}$$

The retail depositor aims to maximize total deposit redemptions. A perceived early default at bank  $i$  implies a positive  $X_{ii}^1$  and a zero  $X_{ii}^2$ ; hence, a retail depositor facing Knightian uncertainty chooses to withdraw whenever she perceives that her bank is potentially defaulting at  $t = 1$  according to condition (11). Formally, for any bank  $i$ ,

$$(12) \quad \Theta_i = \{0, 1\} \Rightarrow W_{ii}^1 = 1.$$

The withdrawal decision (12) is in line with bank run models as well as empirical and experimental evidence. First, the retail depositor withdraws following other depositors of her bank. Chari and Jagannathan (1988) develop a model in which withdrawals of informed depositors provide a signal of bank fundamentals to uninformed depositors of the same bank, causing panic-based runs by the latter. Kiss, Rodriguez-Lara, and Rosa-Garcia (2018) provide evidence that observing withdrawals leads to distorted beliefs that a bank run is underway and causes panic behavior. Second, the retail depositor withdraws when her bank’s correspondent defaults. This behavior reflects contagious runs along liability linkages. By examining the failure of a large Indian bank, Iyer and Peydró (2011) find that banks suffer from large deposit withdrawals when they have high interbank exposure to the failed bank. Brown, Trautmann, and Vlahu (2017) show that withdrawals at one bank may trigger a panic-based run at another bank, especially when the two banks share economic linkages. In our model, liability linkages shape the retail depositor’s perception about fundamentals: if her bank’s correspondent fails, she perceives that her bank could also fail.

In addition to the endogenous withdrawal decisions, retail depositors’ withdrawals may also take place exogenously, as modeled by withdrawal shocks. Let  $\Omega_W$  be the set of banks that face exogenous withdrawals by retail depositors,<sup>27</sup> then for any bank  $i$ ,

$$i \in \Omega_W \Rightarrow W_{ii}^1 = 1.$$

#### D. Payment Equilibrium with Liquidity Withdrawals

**DEFINITION 1:** For a given set of initial balance sheets  $(\mathbf{C}, \mathbf{I}, \mathbf{K}, \mathbf{D})$ , expected and realized investment returns  $(\mathbf{R}^1, \mathbf{R}^2)$ , and withdrawal shocks  $\Omega_W$ , a payment

<sup>26</sup> Depositors know the identity of their bank’s correspondents as a prerequisite to obtaining payment services.

<sup>27</sup> We specify the set  $\Omega_W$  in Section IV. In particular,  $\Omega_W$  is a subset of country banks to reflect fluctuations in liquidity demand outside of financial centers.

equilibrium with liquidity withdrawals consists of the withdrawal decisions  $\mathbf{W}^1$  and payments  $(\mathbf{X}^1, \mathbf{X}^2)$ , such that

- the respondent banks have no incentive to unilaterally deviate from the withdrawal decisions characterized by (8)–(10);
- the retail depositor of each bank has no incentive to unilaterally deviate from the withdrawal decision characterized by (12), given her perceived possible default outcomes of her bank according to (11);
- given the withdrawal decisions  $\mathbf{W}^1$ , the payments of the two periods  $(\mathbf{X}^1, \mathbf{X}^2)$  are mutually consistent and simultaneously solve (2)–(6) for all  $i$  and  $j$ .

The equilibrium concept requires that agents have consistent beliefs about the equilibrium outcome with respect to their information sets. In other words, the respondent banks' belief is consistent with the equilibrium outcome of  $\mathbf{W}^1$ ,  $\mathbf{X}^1$ , and  $E_1[\mathbf{X}^2]$ ; the retail depositor's belief under which she forms her perception is consistent with the equilibrium outcome of  $\mathbf{W}^1$  and  $\mathbf{X}^1$ .

The equilibrium concept also requires that the withdrawal decisions  $\mathbf{W}^1$  and thus the payment equilibrium at  $t = 1$  be consistent with the expected payment equilibrium at the final date. This dynamic consistency requirement is reflected in the term  $E_1[X_{ij}^2]$  in condition (10). Notably, a convenient feature of the model is that backward induction is not necessary to solve the  $t = 1$  equilibrium, as  $E_1[X_{ij}^2] = (1 - W_{ij}^1)D_{ij}$ ,  $\forall j \neq i$ . To see this, suppose for contradiction that a correspondent  $j$  of bank  $i$  is expected to default (i.e.,  $E_1[X_{ij}^2] < (1 - W_{ij}^1)D_{ij}$ ). Then bank  $i$  would have already withdrawn its interbank deposits (following from (9) and (10)), suggesting that  $W_{ij}^1 = 1$  at equilibrium. Hence, all interbank deposits held to maturity must be expected to be paid in full. Notice that all the economically-relevant actions are taken at  $t = 1$ . Given the  $t = 1$  equilibrium and the realizations of  $\mathbf{R}^2$ , the final date payment equilibrium, in turn, is the set of mutually consistent payments  $\mathbf{X}^2$  among the surviving banks from  $t = 1$ .

As is typical in bank run models, self-fulfilling runs can cause multiple equilibria for the  $t = 1$  equilibrium. Notably in our framework, strategic complementarity among depositors' withdrawals ensures that the game satisfies supermodularity. In online Appendix C, we apply results in Tarski (1955), Topkis (1979), Milgrom and Roberts (1990), and Vives (1990), and prove that the model has a unique *best-case equilibrium solution*, which is the outcome with the minimum withdrawals and defaults. We also prove that the unique best-case equilibrium solution can be obtained by an iterative algorithm detailed as follows.

The payment equilibrium is computed in two steps: first the  $t = 1$  equilibrium upon the realization of vector  $\mathbf{R}^1$  and then the  $t = 2$  equilibrium upon the realization of vector  $\mathbf{R}^2$ . The algorithm to compute the  $t = 1$  equilibrium has an outer loop and an inner loop. The outer loop computes the withdrawals  $\mathbf{W}^1$  and the inner loop computes the clearing system  $\mathbf{X}^1$ . We start from an initial guess with the withdrawals being only the exogenous shocks  $\Omega_W$ . Given the withdrawals, we compute the unique clearing matrix using the Eisenberg-Noe fictitious default algorithm. Then we apply the withdrawal decisions (8)–(12) (plugging in  $E_1[X_{ij}^2] = (1 - W_{ij}^1)D_{ij}$ ,  $\forall j \neq i$ ): If the clearing system is consistent with the withdrawals, it is the equilibrium; if, however, more withdrawals are implied, we

update the withdrawal matrix and recompute the clearing matrix. The algorithm terminates in finite steps when no new withdrawals occur. Once the  $t = 1$  equilibrium is determined, we solve the unique  $t = 2$  equilibrium using the Eisenberg-Noe fictitious default algorithm. Online Appendix C contains a detailed description of the algorithm.

The payment equilibrium is a generalization of the clearing system in Eisenberg and Noe (2001) and Acemoglu, Ozdaglar, and Tahbaz-Salehi (2015). Unlike in those two papers, here withdrawals are also part of the equilibrium, determining the liquidity needs of banks. This feature is critical to modeling contagion during the National Banking era. As discussed in Section 1, the interbank liability relationships in the National Banking era were directed along the deposit hierarchy, from country banks to the central reserve city. Contagions could originate from either the top or the bottom of the hierarchy. On the one hand, significant financial shocks to central reserve city banks would force these banks to default, and further cause a cascade of failures, spreading to their respondents in reserve cities and rural areas. On the other hand, significant withdrawal shocks at country banks would force these banks to withdraw from their city correspondents, leading to a cascade of liquidations at their correspondents in reserve cities and the central reserve city. As such, our framework is capable of modeling and quantifying contagion in both types of crises.

#### IV. Quantitative Analysis

In this section, we quantitatively assess the impact of the NBAs on financial stability. To construct the banking systems, we feed the micro-level data on interbank liability relationships and balance sheets into the model and calibrate the model parameters using historical data. We simulate two types of banking crises and compare systemic risk measures for the years before and after the NBAs. Then we compare the baseline results to those from two benchmark models that have no links in one case and near-complete links in another. Finally, we extend the model to assess the impact of banks' actions, such as clearinghouse loan certificates and suspension of cash payments, on financial stability.

We calculate various indicators of financial stability following the literature.<sup>28</sup> The first set of measures comprises the expected percentage of liquidations  $p_l$  and defaults  $p_d$ ,

$$(13) \quad p_l = E_0 \left( \frac{\sum_i \mathbf{1}_i^l}{N} \right), \quad p_d = E_0 \left( \frac{\sum_i (\mathbf{1}_i^{d1} + \mathbf{1}_i^{d2})}{N} \right).$$

Interbank linkages directly determine how contagion spreads; hence, measuring contagion risk through linkages is of central interest to our study. To do so, we

<sup>28</sup>The literature provides a broad set of systemic risk measures as indicators of stability. Freixas, Parigi, and Rochet (2000) and Furfine (2003) analyze the number of bank liquidations, and Cifuentes, Ferrucci, and Shin (2005) report the number of bank failures. Eisenberg and Noe (2001) propose measuring the probability of joint default events in a network. Acharya et al. (2017) define systemic risk as the risk of a crisis in the financial sector and its spillover to the economy at large. De Bandt and Hartmann (2000) define a systemic event as one that affects a considerable number of financial institutions, thereby severely impairing the general well-functioning of the financial system. Glasserman and Young (2015) calculate the total loss in value by summing all nodes.

compute the fraction of liquidations and defaults caused by the propagation of the initial adverse shocks. For instance, if a New York City (NYC) bank faced a sizable exogenous shock in its investment return, this bank's failure might initiate a cascade of liquidations. We then sum the liquidations of all other banks caused by this initial shock.

The second set of measures focuses on the probabilities of joint liquidation and defaults. The term  $\Pr_l^{joint}$  is the probability of joint liquidation when at least  $\theta_l$  fraction of banks liquidate simultaneously. Similarly,  $\Pr_d^{joint}$  is the probability of joint default when at least  $\theta_d$  fraction of banks default simultaneously. The formulas are as follows:

$$(14) \quad \Pr_l^{joint} = \Pr\left(\frac{\sum_i \mathbf{1}_i^l}{N} \geq \theta_l\right), \quad \Pr_d^{joint} = \Pr\left(\frac{\sum_i (\mathbf{1}_i^{d1} + \mathbf{1}_i^{d2})}{N} \geq \theta_d\right).$$

Finally, we also report the magnitude of costs. Let  $V_l$  and  $V_d$  denote, respectively, the expected dollar value of total liquidation and default costs, both normalized by the total value of bank balance sheets of that year. The formulas are as follows:

$$(15) \quad V_l = \frac{E_0[\sum_i \mathbf{1}_i^l (1 - \xi) I_i]}{\sum_i (K_i + \sum_j D_{ji})}, \quad V_d = \frac{E_0[\sum_i \sum_{t=1}^2 \mathbf{1}_i^{dt} (\sum_j W_{ji}^t D_{ji} - A_i^t)]}{\sum_i (K_i + \sum_j D_{ji})}.$$

### A. Constructing the Banking Systems

We construct the banking systems by obtaining the values of balance sheet items (**C, I, K, D**) from our data.<sup>29</sup> Vault cash, **C**, comes from the standardized balance sheet item *Cash*. Equity capital, **K**, equals *Capital* plus *Surplus*. The variable for retail deposits and banknotes,  $D_{ii}$ , is constructed by adding *Deposits* and *Notes*. Interbank network, **D**, is constructed from the micro-level due-from data, where  $D_{ij}$  is the dollar value of interbank deposits of bank  $i$  due from bank  $j$ . Finally, we back out the level of investment in loans and securities, **I**, from the balance sheet equation: *Investment* = *Equity capital* + *Retail deposits and banknotes* + *Deposits due to banks* – *Vault cash* – *Deposits due from banks*.<sup>30</sup>

To discipline the process for investment returns (1), we estimate the vector of average investment returns,  $\mathbf{R}^0$ , and the covariance matrix,  $\Sigma$ . From the balance sheet data of 1862 and 1867, we obtain the three subitems for “investment in loans and securities”: loans, government securities, and other securities. This decomposition provides us with an estimate of the portfolio weights in these three assets for the two years.<sup>31</sup> To proxy for the assets returns, we use the historical return

<sup>29</sup>Detailed descriptions of balance sheet items are available in Section II. Online Appendix A2 describes the method of balance sheet standardization for state and national banks.

<sup>30</sup>Although we can directly obtain investment from the balance sheet data, the raw data do not necessarily satisfy the balance sheet equation for two reasons. First, for regulatory purposes, certain assets on the state banks' balance sheets, such as “due from brokers” and “due from directors,” were not counted toward total assets. Second, the original balance sheets contain items difficult to categorize, such as “not included under either of the above headings.”

<sup>31</sup>To estimate the investment returns of each bank, one would ideally have information on the riskiness of the borrowers and detailed accounts of securities holdings. Because data at such a granular level are not available, we

series reported in Snowden (1990). In particular, we use the annual inflation-adjusted returns for commercial paper, government bonds, and all stocks. To focus on the non-crises periods in the National Banking era, we use data from 1872 (the earliest year available) to 1912 and exclude the five crises years (1873, 1884, 1890, 1893, and 1907). These return series combined with each bank's portfolio weights allow us to estimate the average return vectors,  $\mathbf{R}^0$ , and covariance matrices,  $\Sigma$ , for the 1862 and 1867 banking systems. Averaging across all banks, the estimated annual average, standard deviation, and correlation coefficient for the year 1862 are 6.44 percent, 4.09 percent, and 0.76; those for the year 1867 are 5.36 percent, 3.19 percent, and 0.87.

Parameter  $\xi$  represents the recovery rate at which banks liquidate their investments. Records for liquidation costs are limited for the National Banking era. Fire sales did not occur during banking crises because banks could suspend payments to depositors in the case of bank runs. As an alternative, we estimate the recovery rate of insolvent banks by receivers during the period. We use information on the liquidation of California state banks that failed during the Panic of 1893 (see Board of Bank Commissioners of the State of California 1893). We compare the investment values of failed banks before the panic and upon the completion of the liquidation process, provided that the liquidation period lasted at least one year. On average, receivers were able to recover 58.17 percent of the original investment value. This provides us with an estimate of the recovery rate, i.e.,  $\xi = 0.5817$ .

Parameters  $\theta_l$  and  $\theta_d$  define the thresholds for systemic liquidation and default events. The goal is to obtain a "quantitatively relevant quantile" for what was considered a systemic liquidation/default event in the National Banking era. Again, the exact empirical counterparts for these parameters are absent: banks did not have to liquidate during the banking panics of the National Banking era because they were allowed to suspend cash payments. The suspended banks would have otherwise liquidated their assets. Hence, the closest empirical counterparts for these quantiles during systemic banking crises in that period would be the fraction of simultaneously suspended banks and the fraction of simultaneously (permanently) closed banks. We use information on bank suspensions and permanent closures in five states that experienced severe bank runs during the Panic of 1893: California (Office of the Attorney General of the State of California 1894), Colorado, Montana, Oregon, and Washington (Carlson 2005).<sup>32</sup> We compute the percentages of suspended banks and permanently closed banks, average across the five states, and obtain  $\theta_l = 0.1378$  and  $\theta_d = 0.0433$ .

### B. Simulating Banking Crises

As discussed in Section IB, we can divide the banking crises from the National Banking era into two types based on the origin of shocks. The first type began with investment losses in NYC and spread to the rest of the country, from the top to the

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implicitly assume that there are three asset classes and that banks only differ by the portfolio weights. Additionally, the portfolio weights are fixed like in the balance sheets of 1862 and 1867.

<sup>32</sup>To a large extent, the Panic of 1893 did not affect Pennsylvania banks. The only panic that truly had an impact on Pennsylvania banks was the Panic of 1873; however, the data available for 1873 do not make a distinction between temporary suspensions and permanent failures.

bottom of the reserve hierarchy; we refer to this type as the *top-to-bottom crises*. The second type began with liquidity shortages at banks outside financial centers. Massive withdrawals of interbank deposits by country banks overwhelmed the ability of city correspondents to meet the demand. Liquidity shortages originated from the bottom of the reserve hierarchy and spread to the top; we refer to this type as the *bottom-to-top crises*. Next, we study how bank networks would have contributed to banking crises in the National Banking era by simulating the two types of crises.

*Top-to-Bottom Crises.*—For top-to-bottom crises, we simulate the scenario in which NYC banks expect to have correlated losses in loans and securities investments. Parameter  $\Delta R_{NYC}^1$  is the reduction in expected investment rates for all NYC banks and governs the size of the top-to-bottom shock. To calibrate the maximum shock size, we turn to the historical returns of the stock market. Among the five major banking crises, the stock market suffered the heaviest losses in the Panic of 1907, with an annual return rate of  $-25.32$  percent. Accordingly, we vary the magnitude of  $\Delta R_{NYC}^1$  from 0 to 0.30.<sup>33</sup> For each value of  $\Delta R_{NYC}^1$ , we simulate 5,000 panels of investment returns  $(\mathbf{R}^1, \mathbf{R}^2)$  using the estimated  $\mathbf{R}^0$  and  $\Sigma$ . After we impose negative shocks to NYC banks, the expected returns for NYC banks at  $t = 1$  become  $R_{NYC}^1 - \Delta R_{NYC}^1$ ; return rates for all other banks remain unchanged. With the simulated return rates, we plug in the empirical data on balance sheets and interbank deposits, solve for the two-period payment equilibrium, and compare the financial stability measures in 1862 and 1867.

Figure 3 shows the systemic risk measures for the simulated top-to-bottom crises. The horizontal axis indicates the size of the shock  $\Delta R_{NYC}^1$ . The six panels, respectively, plot the systemic risk measures:  $p_b, p_d, \Pr_l^{joint}, \Pr_d^{joint}, V_b$ , and  $V_d$ . Solid-black curves with circles and plus signs represent, respectively, the measures before and after the NBAs. All measures are expressed as percentages. When the shock size is small, for instance, when the expected investment return at an NYC bank is reduced by 10 percent (i.e., the average return rate for an NYC bank decreases from around 6 percent to  $-4$  percent), all systemic risk measures for 1867 are close to zero and lie below those of 1862. However, with a shock size as large as 30 percent, all measures of 1867 exceed those of 1862.

Our results show that, for top-to-bottom crises, the shock size is a critical determinant of the resilience of bank networks. As long as the magnitude of the negative shocks is within a threshold, the post-NBAs network is more resilient. However, when losses are large enough to trigger liquidation at financial center banks, concentrated linkages start to serve as channels for systemic contagion; consequently, systemic risk measures in 1867 exponentially increase whereas those for 1862 are less responsive.

The post-NBAs network is more robust against mild shocks, and the underlying mechanism is a drop in contagion. The contagion measures, represented by the dashed-gray curves in panels A and B, illustrate the expected percentage of

<sup>33</sup> During the National Banking era, national banks in NYC held almost 40 percent of their outstanding loans in the form of call loans. The call loan market served as a source of funds for margin borrowing on the New York stock market through arrangements between banks and brokers (Tallman and Moen 2003). The large exposure of these banks to the call market made them vulnerable to instability from the stock market that resulted in the devaluation of call loan assets.



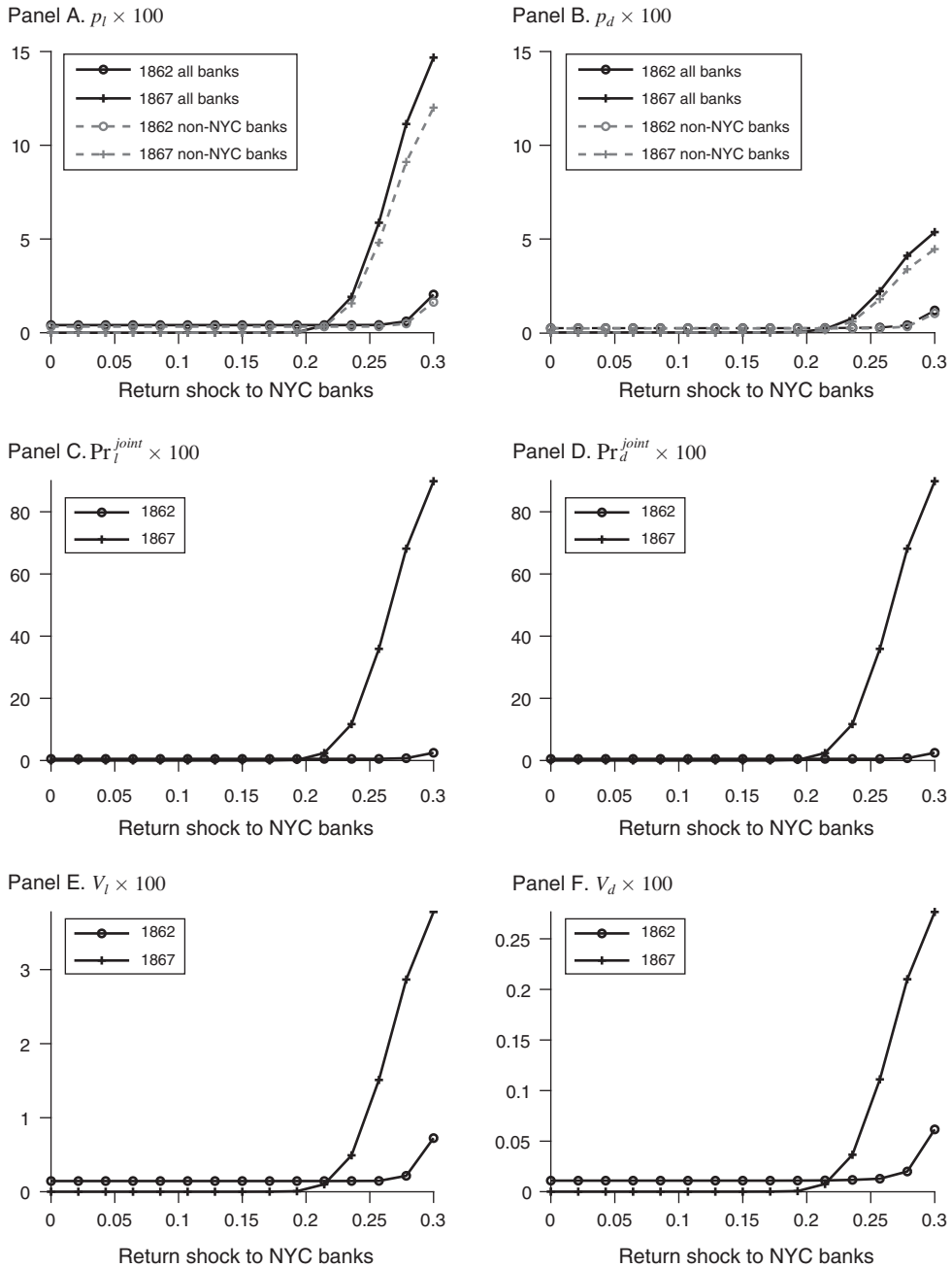


FIGURE 3. TOP-TO-BOTTOM CRISES: SYSTEMIC RISK MEASURES

Notes: This figure shows the financial stability measures for simulated top-to-bottom crises. The horizontal axis is the size of  $\Delta R_{NYC}^1$ , i.e., the reduction in expected investment rates for all NYC banks. Panels A–F plot, respectively, the expected percentage of liquidations,  $p_l$ ; the expected percentage of defaults,  $p_d$ ; the probability of a systemic liquidation event,  $\text{Pr}_l^{\text{joint}}$ ; the probability of a systemic default event,  $\text{Pr}_d^{\text{joint}}$ ; and the expected liquidation and bankruptcy costs normalized by the total value of the banking sector,  $V_l$  and  $V_d$ . All measures are expressed as percentages. Solid-black curves with circles represent the measures before the NBAs (1862), and solid-black curves with plus signs represent the measures after the NBAs (1867). In addition, the dashed-gray curves in panels A and B represent the expected percentages of liquidations and defaults at banks not located in NYC and thus not directly shocked by return reductions.

liquidations and defaults at banks not located in NYC. These banks are not directly shocked; hence, the liquidations and defaults are likely caused by their direct or indirect liability relationships with shocked NYC banks. When the expected returns of NYC banks are reduced slightly, say by 10 percent, a more concentrated network reduces contagion for two reasons. First, as the counterparty chains shorten (from an average length of 3 in 1862 to 1.8 in 1867), the chances of contagion from indirect counterparties are lower. Second, concentration increases the number of respondents each NYC correspondent has. This facilitates risk diversification because only a small fraction of loss felt by the correspondent is passed on to individual respondents per the *pro rata* payment rule.

Once the adverse shocks are sizable, contagious liquidation becomes more pronounced in the post-NBAs network. Under substantial losses, NYC banks default on their respondents, causing withdrawals and illiquidity in a systemic fashion downstream. As such, the concentrated interbank network acts as a mechanism for contagion.<sup>34</sup> Using the 12-bank example network introduced in Section II (see Figure 1), we demonstrate how the concentration of deposit relationships toward the American Exchange Bank influences its systemic importance. We shock the American Exchange Bank with a significant investment loss. As shown in Figure 4, no bank liquidates in 1862 as the American Exchange Bank (the polka-dotted node) was not very connected. In 1867, however, financial distress spreads to five other banks (colored in black) directly and indirectly linked to American Exchange; this is a typical example of interbank contagion.

This phase transition of financial stability confirms the “robust-yet-fragile” nature of the interbank network in Acemoglu, Ozdaglar, and Tahbaz-Salehi (2015); it shows that the “knife-edge dynamics” highlighted in Haldane (2013) also manifest in the historical bank networks.

*Bottom-to-Top Crises.*—For bottom-to-top crises, we simulate the scenario in which a subset of country banks experiences exogenous withdrawal requests from their retail depositors. In particular, we randomly draw a subset of country banks,  $\Omega_w$ , and set  $W_{ii}^1 = 1, \forall i \in \Omega_w$ . The set  $\Omega_w$  follows a multivariate Bernoulli distribution with two parameters: the probability,  $\Omega_w^p$ , and correlation,  $\Omega_w^o$ . A positive correlation,  $\Omega_w^o$ , is consistent with the observation that the demands for money were highly correlated, peaking during fall and spring planting seasons. To calibrate these two parameters, we match the simulated moments of equilibrium deposit withdrawals to the observed deposit contractions during the Panic of 1893, the most severe liquidity crisis to have originated from rural areas. Particularly, we match deposit contractions in Michigan, a state that experienced severe bank runs. Between December 9, 1892, and December 19, 1893, retail deposits held by country banks and interbank due-to deposits held by all banks shrank by 20.65 percent and 36.21 percent, respectively.<sup>35</sup> Matching the moments implies a correlation coefficient of  $\Omega_w^o = 0.498$  and a maximum probability of  $\Omega_w^p = 0.060$ . A value of  $\Omega_w^p$  lower than 0.06 implies

<sup>34</sup>In online Appendix D, we illustrate these economic forces by analytically comparing an  $N$ -bank chain network versus a two-tier pyramid.

<sup>35</sup>We use information on Michigan because the annual reports provided the magnitude of bank runs during a short interval. Deposits held by Michigan country banks decreased from \$61,089,421 on December 9, 1892 to \$48,477,265 on December 19, 1893. Within the same interval, deposits due to banks and bankers at Michigan banks

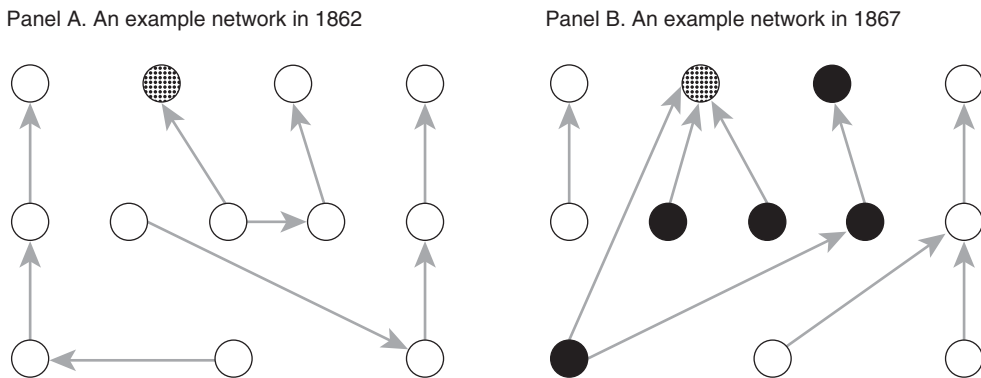


FIGURE 4. TOP-TO-BOTTOM CRISIS: A 12-BANK EXAMPLE NETWORK

Notes: This figure uses the 12-bank example network (identified in Figure 1) to show the degree of contagion when the American Exchange Bank (polka-dotted node) is shocked with a big investment loss. The black nodes indicate banks that suffer from liquidation and the white nodes indicate those that are free from liquidation.

less-severe deposit withdrawals. For example, when setting the probability parameter equal to 0.024, the simulated moments match the outcomes for California banks in 1893.<sup>36</sup>

In the simulation, we vary the magnitude of  $\Omega_W^p$  from 0 to 0.06. For each value of  $\Omega_W^p$ , we simulate the investment returns  $(\mathbf{R}^1, \mathbf{R}^2)$  and the withdrawal sets  $\Omega_W$  for 5,000 times. For each simulated scenario, we solve for the two-period payment equilibrium and compare the financial stability measures in 1862 and 1867.

Figure 5 shows the systemic risk measures for the simulated bottom-to-top crises. The horizontal axis indicates the size of the shock  $\Omega_W^p$ . The six panels, respectively, plot the systemic risk measures:  $p_l, p_d, \Pr_l^{joint}, \Pr_d^{joint}, V_l,$  and  $V_d$ . Solid-black curves with circles and plus signs represent, respectively, the measures before and after the NBAs. All measures are expressed as percentages. The results show that the 1867 banking system is more robust to liquidity shocks originating from country banks. All systemic risk measures for 1867 lie below those for 1862, regardless of the size of the shock.

For a bottom-to-top crisis, the concentrated network that evolved post the NBAs is always more robust. The interbank links can still propagate contagious withdrawals upward along the pyramid. Nonetheless, the financial center banks hold more liquid assets and thus are more capable of withstanding massive withdrawals. As long as the financial center banks stay solvent, the depositors' runs are only limited to the shocked country banks and their direct correspondents. The concentrated pyramid structure effectively avoids the propagation of withdrawal shocks, so banks that are not directly shocked can avert liquidation.

decreased from \$11,816,187 to \$7,537,397 (Commissioner of the Banking Department of the State of Michigan 1892–1893).

<sup>36</sup>Using the deposit records of January 1893 and July 1893 from Board of Bank Commissioners of the State of California (1893), we calculate that the retail deposits at country banks shrank by 10.75 percent, and the interbank due-to deposits at all banks shrank by 20.40 percent in California.

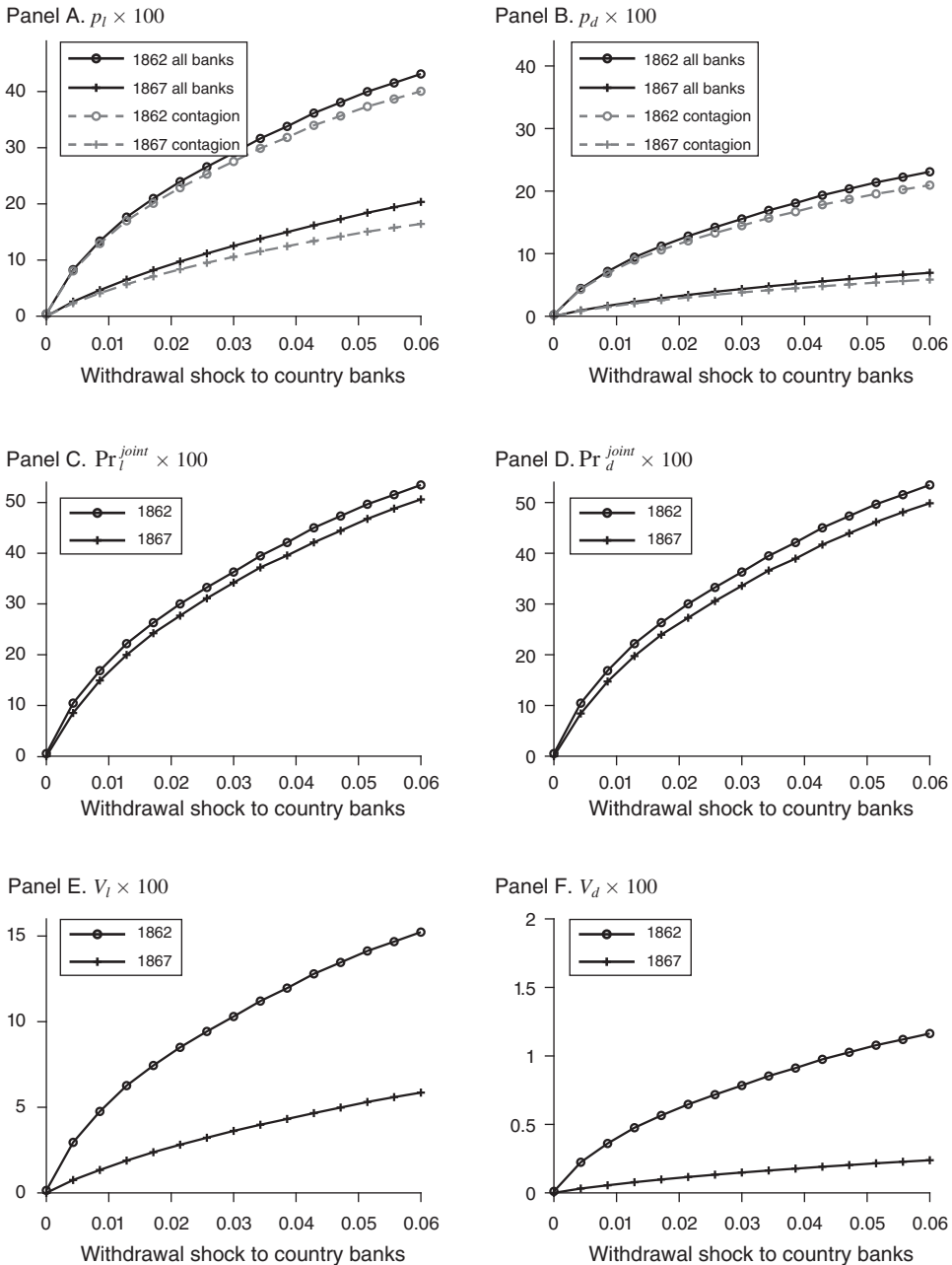
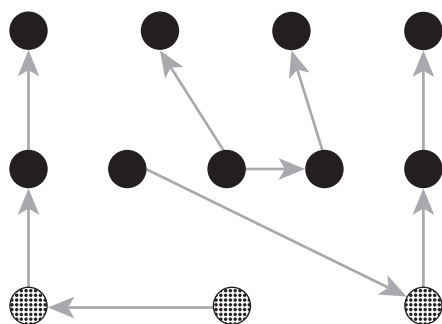


FIGURE 5. BOTTOM-TO-TOP CRISES: SYSTEMIC RISK MEASURES

Notes: This figure shows the financial stability measures for simulated bottom-to-top crises. The horizontal axis is the size of  $\Omega_W^p$ , i.e., the exogenous probability of retail depositors' withdrawal shocks at country banks. Panels A–F plot, respectively, the expected percentage of liquidations,  $p_l$ ; the expected percentage of defaults,  $p_d$ ; the probability of a systemic liquidation event,  $\Pr_l^{joint}$ ; the probability of a systemic default event,  $\Pr_d^{joint}$ ; and the expected liquidation and bankruptcy costs normalized by the total value of the banking sector,  $V_l$  and  $V_d$ . All measures are expressed as percentages. Solid-black curves with circles represent the measures before the NBAs (1862), and solid-black curves with plus signs represent the measures after the NBAs (1867). In addition, the dashed-gray curves in panels A and B represent the expected percentages of liquidations and defaults at banks not directly shocked by exogenous withdrawals.

Panel A. An example network in 1862



Panel B. An example network in 1867

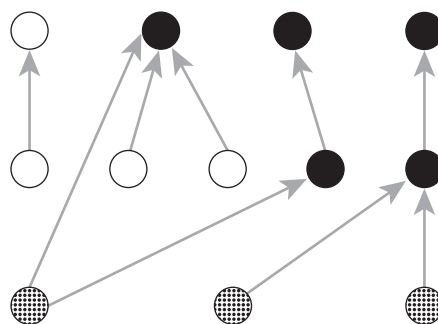


FIGURE 6. BOTTOM-TO-TOP CRISIS: A 12-BANK EXAMPLE NETWORK

*Notes:* This figure uses the 12-bank example network (identified in Figure 1) to show the degree of contagion when country banks (polka-dotted nodes) face exogenous withdrawal shocks. The black nodes indicate banks that suffer from liquidation and the white nodes indicate those that are free from liquidation.

The economic mechanism manifests once again in the 12-bank example network. To illustrate the crises that originate from liquidity shortages at banks outside financial centers, we shock all three country banks (the polka-dotted nodes in Figure 6). The 1862 subnetwork is vulnerable to the withdrawal shocks with all banks eventually suffering from liquidation. Conversely, the four banks not directly connected to the country banks in 1867 are safe from liquidation, consistent with the economic forces discussed above.

*Implications for Sources of Bank Panics.*—From the counterfactual analysis, the regulations brought by the NBAs seem to have increased the systemic nature of top-to-bottom crises, but not the systemic nature of bottom-to-top crises. This result adds to the discussion on sources of bank panics during the National Banking era. Many have long believed that bank panics originated with banks outside financial centers (e.g., Sprague 1910; Kemmerer 1910, 1911; Miron 1986; Champ, Smith, and Williamson 1996).<sup>37</sup> Our findings show that financial center banks would have become more resilient to financial distress coming from country banks, but the same is not true for country banks when the financial centers suffered from liquidity shortages. This further suggests that shocks to financial center banks would have been a greater threat to financial stability.

Indeed, recent studies of the National Banking era provide evidence that significant financial shocks in NYC may have been a more important source of the crises.<sup>38</sup> As in Wicker (2006), with the sole exception of 1893, banking panics had their origin in the central money market and from there spread to the interior.

<sup>37</sup> Sprague (1910, pp. 18–19), for instance, argues that the “pyramiding of reserves” made the NYC banks vulnerable to withdrawal by banks outside financial centers: “It is clear, then, that with this situation in New York an emergency would cause serious disturbance if it should lead to the withdrawal of any considerable amount by the outside banks... Every year furnished ample evidence that the outside banks had a strong preference for reducing their balances with agents rather than their own cash reserves when their depositors resorted to them for even very moderate supplies of money.”

<sup>38</sup> See, for example, Tallman and Moen (1995); Wicker (2006); Bruner and Carr (2008); Frydman, Hilt, and Zhou (2015); Calomiris and Carlson (2017); and Anderson and Bluehorn (2017).

Bank failures in rural areas did not have nationwide effects because rural bank closures were few in number and region specific. Empirical evidence suggests that the national banking system was more robust to mild shocks but more fragile to large shocks to NYC banks. Anderson and Bluedorn (2017) study how the banking system reacted when NYC banks faced mild shocks during the Panic of 1884; they find that financial distress did not reach Pennsylvania. The banking system reacted differently when NYC banks faced major shocks. Calomiris and Carlson (2017) show that the suspensions of NYC banks during the Panic of 1893 caused liquidity issues at interior banks in the West. Frydman, Hilt, and Zhou (2015) examine the Panic of 1907 and find that initial losses that originated from NYC led to reduced corporate investments at connected institutions and suspensions at commercial banks throughout the country.

*Benchmarks: Empty and Near-Complete Networks.*—The interbank networks in 1862 and 1867 are sparse and incomplete. Each respondent bank had only one or very few correspondent relationships. These relationships were shaped by regulation changes, trade patterns, and transportation linkages (such as canals and railroads). The theory literature on the stability of incomplete networks has potentially conflicting views (e.g., Allen and Gale 2000; Freixas, Parigi, and Rochet 2000; Blume et al. 2011).<sup>39</sup> To evaluate how the banking system performs, we next compare the baseline results to those from two benchmark networks: (i) an empty network in which banks operate in isolation and have no interbank deposits and (ii) a near-complete network in which banks have numerous connections.

We construct the empty network by eliminating the interbank deposits. Specifically, we set each interbank deposit to zero,  $D_{ij} = 0, \forall i \neq j$ . We then adjust the size of cash to ensure that the balance sheet equality still holds. For example, had a country bank not placed deposits at a correspondent, it would hold extra cash to satisfy the reserve ratio.

Because correspondent relationships were directed along the deposit hierarchy, from country banks to the central reserve city, a complete network is not economically meaningful; instead, we construct the near-complete network by redistributing the total due-from deposits of a respondent bank to all the banks in the same location as its actual correspondents. Banks in the resultant benchmark network have more numerous correspondent relationships, and the linkages are much denser.

Figure 7 plots the financial stability measures for the two benchmark networks in top-to-bottom crises (panels A and C) and bottom-to-top crises (panels B and D). For comparison, we also include the measures for the actual original networks in Figures 3 and 5. Results are robust across all measures, and we only show the expected percentages of liquidations. We make the following observations by comparing the results in the two benchmarks to the original networks. First, the empty network has close to zero systemic risks. Interbank linkages play two roles: they leverage up the banks by inflating the size of their balance sheets, and they create channels for contagion. Once we remove the links, the channel for contagion is

<sup>39</sup> Allen and Gale (2000) and Freixas, Parigi, and Rochet (2000) show that incomplete networks are more prone to contagion than complete structures. In contrast, Blume et al. (2011) show that networks with dense connections are more susceptible to cascading failures.

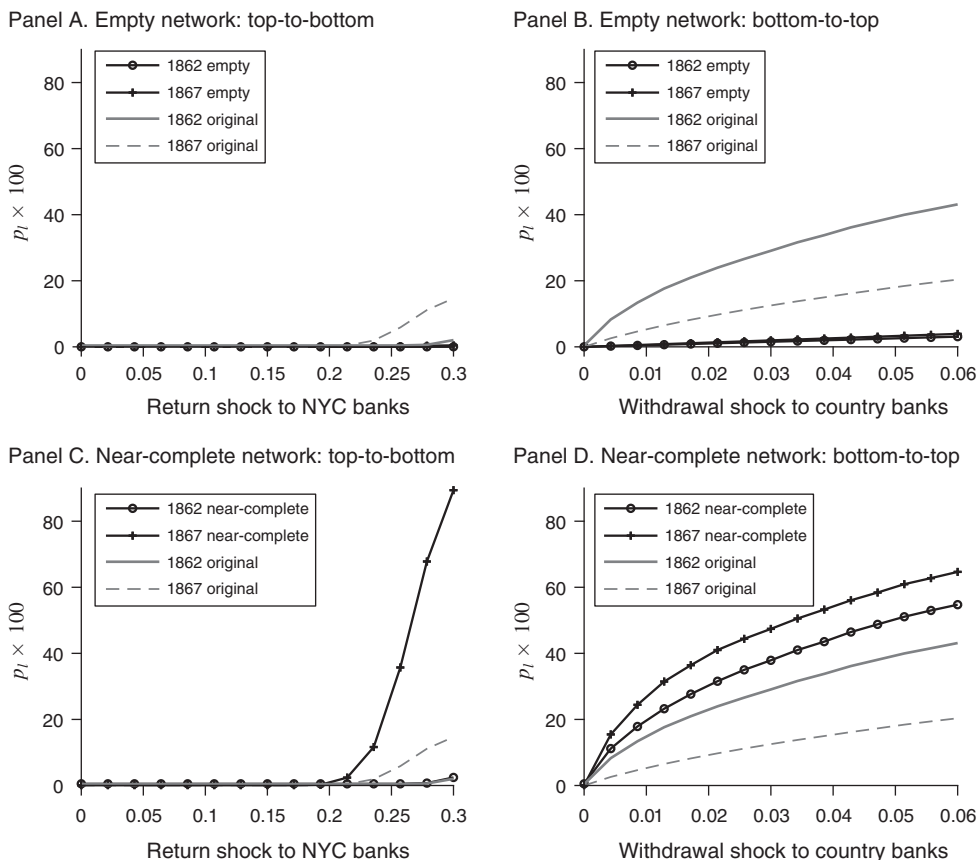


FIGURE 7. SYSTEMIC RISK MEASURES IN TWO BENCHMARKS

Notes: This figure shows the financial stability measures for two benchmark networks. Panels A and B plot the expected percentages of liquidations  $p_l$  for an empty network in top-to-bottom crises and bottom-to-top crises, respectively. Panels C and D plot the same measures for a near-complete network in the two types of crises. Solid-black curves with circles represent the measures before the NBAs (1862), and solid-black curves with plus signs represent the measures after the NBAs (1867). In all panels, we also plot the results from the original networks: the 1862 network in solid-gray curves and the 1867 network in dashed-gray curves.

absent, and idiosyncratic risk no longer becomes systemic. Importantly, when banks operate in isolation, a change in regulation does not affect systemic risk. Second, the near-complete network has significantly higher systemic risk owing to enormous contagion. For a top-to-bottom crisis, the importance of financial center banks remains, and the robust-yet-fragile result holds. For a bottom-to-top crisis, the 1867 measures are much higher: with denser connections along the reserve pyramid, withdrawal shocks have a much wider reach. Overall, these exercises show that the interbank linkages are a major driver for contagion and that the effect of regulation depends crucially on the underlying networks.

### C. New York City Banks' Reaction to the Crises

Lacking a formal lender of last resort, banks responded to crises by acting collectively, through a single institution called a clearinghouse. The clearinghouse issued

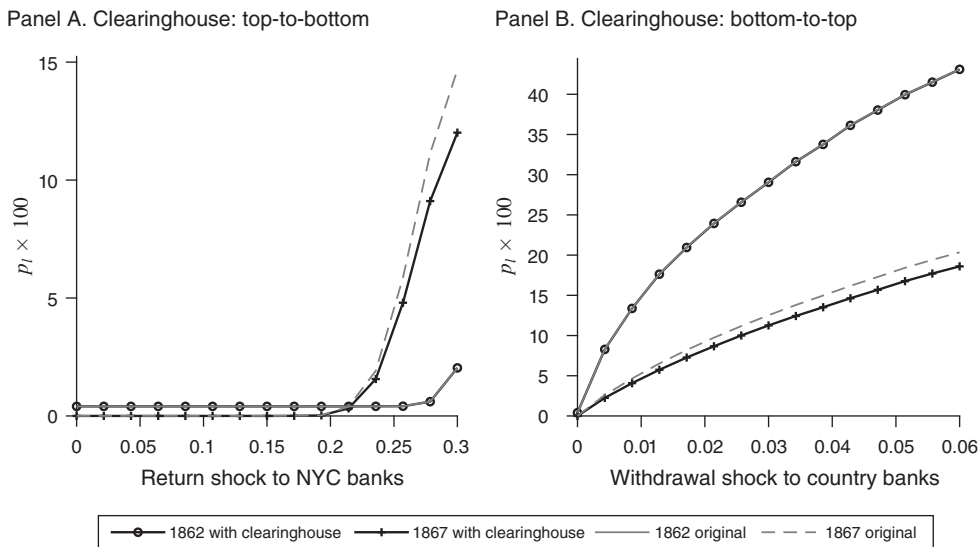


FIGURE 8. CLEARINGHOUSE LOAN CERTIFICATES

*Notes:* This figure shows the financial stability measures when we allow NYC banks to issue clearinghouse loan certificates to member banks. Panels A and B plot the expected percentages of liquidations  $p_i$  in top-to-bottom crises and bottom-to-top crises, respectively. Solid-black curves with circles represent the measures before the NBAs (1862), and solid-black curves with plus signs represent the measures after the NBAs (1867). In both panels, we also plot the results from the original setup: the 1862 network in solid-gray curves and the 1867 network in dashed-gray curves.

loan certificates to create private money and alleviate liquidity shortages. When the issuance of loan certificates could not contain the crisis, banks jointly suspended the convertibility of deposits. Next, we discuss how these actions would have affected financial stability.

*Clearinghouse Loan Certificates.*—We extend the baseline model to allow NYC banks to issue clearinghouse loan certificates to member banks to share liquidity risk. If the total liquidity surplus of NYC banks that do not experience a liquidity shortage exceeds the total liquidity shortage of those that do, then loan certificates are issued to members. As a result, all NYC banks could stave off systemic liquidations. We keep the rest of the model and the calibration as in the baseline analysis.

Figure 8 shows that the systemic risk measures are lower for the post-NBAs network compared to the original setup without clearinghouse loan certificates, whereas the reductions are insignificant for the pre-NBAs network. The clearinghouse loan certificates issued to NYC banks facilitate risk sharing, by allowing liquidity-rich banks to reallocate their excess liquidity to those that are close to liquidation. Risk-sharing relationships unambiguously reduce liquidation risk among NYC banks and thus differ from liability links that cause contagion. While our results confirm the value of risk sharing in hedging idiosyncratic liquidity risks, the small magnitudes of risk reduction indicate that the effect of clearinghouse loan certificates is quite limited because financial center banks faced correlated shocks.

*Suspension of Convertibility.*—When facing massive withdrawals, a bank can temporarily suspend payments to stop a run; this is referred to as the *suspension*



*of convertibility*. Cash suspensions could have opposing effects on systemic risk. NYC banks can avoid liquidation by suspending convertibility. The anticipation of this action further prevents depositors from withdrawing prematurely. Alternatively, NYC banks hold the majority of interbank deposits, so when they cannot honor the withdrawal requests of their respondents, liquidity shortages spread to respondents in other cities, generating contagion.

We extend the model to incorporate cash suspensions. An NYC bank invokes the suspension of convertibility when its liquid assets (vault cash plus redeemed interbank deposit) fail to meet its liquidity withdrawal requests. Suspensions guarantee that liquidations will not happen at NYC banks; hence, the withdrawal conditions no longer apply to suspending banks. We keep the rest of the model and the calibration as in the baseline analysis.

Figure 9 shows that the systemic risk measures are lower than those in the original setup without the suspension of convertibility. This observation implies that the benefit of suspension in reducing liquidations at NYC banks and preventing runs dominates the contagion downside. Compared with the previous extension using the clearinghouse loan certificates, the halt of liquidations at NYC banks is unconditional; hence, the liquidation measures are lower. Our findings on the systemic risk impact of more concentrated bank networks remain robust when allowing for these actions taken by NYC banks.

## V. Conclusion

The 2007–2009 financial crisis sparked a growing recognition of how interconnected financial architecture affects financial stability. In response, policymakers and regulators have devised rules aimed at avoiding another systemic crisis by limiting exposures between banks. Yet, very little study has been done to understand how bank regulations affect financial architecture and systemic risk.

In this paper, we examine how the National Banking Acts (NBAs) of 1863 and 1864 changed bank networks and affected financial stability. The NBAs created reserve requirements that dictated the amounts and locations of interbank deposits. We begin by documenting the topology of bank networks before and after the enactment of the NBAs. Then we perform “stress tests” on the networks to assess how vulnerability to particular types of shocks evolved because of the regulation change. This exercise sheds light on how an important bank regulation could reshape the extent and nature of financial fragility.

We find that a reserve pyramid with three distinct tiers emerged after the NBAs and that the interbank linkages became more concentrated in a small number of financial center banks, creating systemically important institutions. Using counterfactual analysis, we find that the NBAs would have created a “robust-yet-fragile” network. A greater concentration of links would have led to a more robust interbank network during normal times. However, a greater concentration of links would have also increased the likelihood of contagion when highly interconnected financial center banks faced large shocks.

Our findings have new insights for financial regulations that mandate the central clearing of over-the-counter derivatives. Despite the intention to mitigate bilateral counterparty risk, this regulatory change also has radically reshaped the

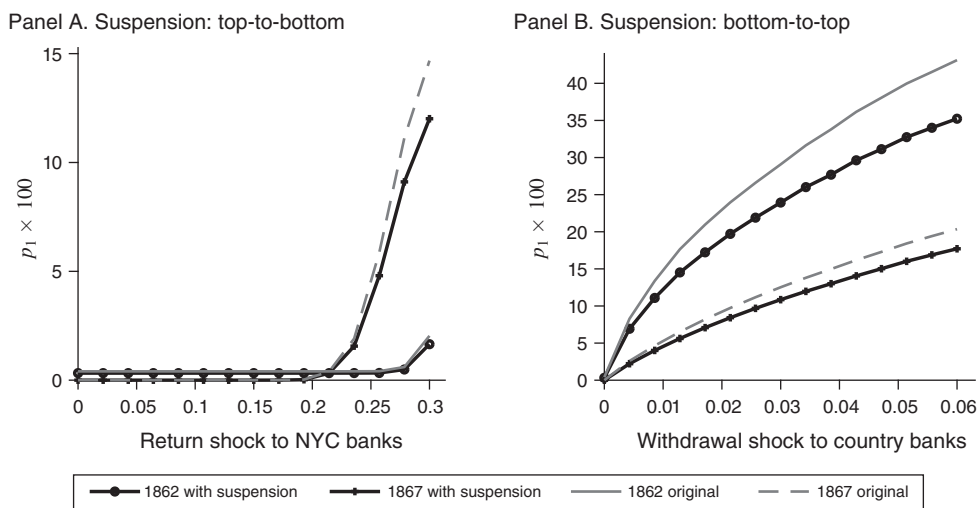


FIGURE 9. SUSPENSION OF CONVERTIBILITY

*Notes:* This figure shows the financial stability measures when we allow NYC banks to suspend cash payments. Panels A and B plot the expected percentages of liquidations  $p_i$  in top-to-bottom crises and bottom-to-top crises, respectively. Solid-black curves with circles represent the measures before the NBAs (1862), and solid-black curves with plus signs represent the measures after the NBAs (1867). In both panels, we also plot the results from the original setup: the 1862 network in solid-gray curves and the 1867 network in dashed-gray curves.

interconnected structure of banks and raised risk concerns about the systemic importance of CCPs. By analyzing a regulatory change to a historical banking system that is structurally similar to the effect of mandatory central clearing, our study highlights the persistence of the “too-connected-to-fail” problem.

Our study leaves open several areas for further investigation. One is how the results of this research translate to the Federal Reserve System. A lender of last resort would have relieved banks’ liquidity problems and reduced systemic risk. At the same time, the presence of the Federal Reserve could have increased systemic risk because bailouts can encourage risk taking. A related area of research is what bank networks looked like after the Federal Reserve was introduced. Recent studies have reported that interbank networks played an important role in amplifying shocks during the Great Depression. It would be interesting to examine the structure of bank networks and understand why networks continued to play such a role. Last, but not least, financial institutions are interconnected with various types of contracts in the modern world; it would be interesting to understand how disruptions in payment networks could spill over to other markets in the present day.

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