Un-Networking: The Evolution of Networks in the Federal Funds Market

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Abstract

Using a network approach to characterize the evolution of the federal funds market during the Great Recession and financial crisis of 2007-2008, we document that many small federal funds lenders began reducing their lending to larger institutions in the core of the network starting in mid-2007. But an abrupt change occurred in the fall of 2008, when small lenders left the federal funds market en masse and those that remained lent smaller amounts, less frequently. We then test whether changes in lending patterns within key components of the network were associated with increases in counterparty and liquidity risk of banks that make up the core of the network. Using both aggregate and bank-level network metrics, we find that increases in counterparty and liquidity risk are associated with reduced lending activity within the network. We also contribute some new ways of visualizing financial networks.

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1 Introduction

For many years, a few stylized facts regarding banking flows were pretty reliable. As far back as the mid-1800s, regional or country banks with an excess of funds would sell them to large banks in the cities, which used them, in part, to fund new loans to businesses and individuals (Mitchener and Richardson (2013)). This construct was even part of the reason why the Federal Reserve System was established – in order to promote and maintain an efficient transfer of funds in the banking system. Often, one large bank would buy funds from many smaller banks, and then the larger banks would connect to each other and settle transactions either through a central clearinghouse, or later, through the Federal Reserve.

Even with the consolidation of the banking industry during the 1980s and 1990s, and the innovation of interstate branching in 1995, large banks bought excess deposits held at the Federal Reserve from smaller banks. The "federal funds market," or the market for cash balances held by institutions at the Federal Reserve, was an active, unsecured overnight market (Board of Governors of the Federal Reserve System (2005), Stigum and Crescenzi (2007)). In particular, through about 2007, there were many more lenders than borrowers in the federal funds market, and the lenders tended to be smaller institutions, while the borrowers were larger ones.

Everything changed with the advent of the financial crisis in mid-2007, as many of the smaller lenders reduced their lending to the larger institutions in the core of the network. Using network analysis, we find that the federal funds network began to contract rapidly and change dramatically in structure after the Lehman Brothers' bankruptcy in the fall of 2008. The number of participating banks and transactions plummeted, as did overall dollar volume. This paper carefully analyzes the factors that caused this change in banking flows, focusing on the role of counterparty and liquidity risk. Using both aggregate and bank-level network metrics, we find evidence that both counterparty and liquidity risk played a key role in determining lending behavior within the network. We also develop a novel network visualization tool: an animated 3-dimensional diagram which shows the evolving linkages between the various components of the network.

The paper proceeds as follows. Section 2 gives background and historical information on the federal funds market and payment flows. Section 3 describes the data we use and discusses our analytical framework. Section 4 discusses the federal funds market from a network perspective. Using these characteristics, section 5 reviews our aggregate results, and section 6 explores our institution-level analysis. Section 7 concludes.

2   Related Literature

The literature has noted evidence of both heightened counterparty risk and increased liquidity hoarding in the federal funds market around the time of the 2008 financial crisis. Some works have focused on more general trends. For example, Williams and Taylor (2009) use a no-arbitrage model of the term structure to explain why the spread between interest rates on term lending and overnight federal funds lending began to grow in August 2007. Their results indicate that expectations of future interest rates and counterparty risk drove the spread, with liquidity concerns playing a negligible role.

Other literature uses data similar to the data we use in this paper. For example, employing Fedwire data, Ashcraft, Mcandrews, and Skeie (2011) examine the behavior of the federal funds market during the 2007-2008 financial crisis and find evidence of precautionary holdings of reserves. They distinguish large banks from small banks based on the average volume of each bank's daily Fedwire payments. The authors find that small banks are typically net lenders who lend mostly between 3pm and 5pm when faced with unusually large intraday balances. In contrast, large banks both lend and borrow throughout the day, but are typically net borrowers. They also find that banks that had larger payment shocks (non-loan Fedwire net sends) held larger precautionary reserves, particularly those that sponsored ABCP conduits. To determine whether counterparty risk constrained lending during the crisis, they examine changes in the distribution in the number of banks a borrower funded itself with, and the distribution in the number of counterparties that lenders lent to. Although the distribution in the number of borrowers was little changed during the crisis, they find some evidence that banks began lending to fewer counterparties in the fall of 2008, suggesting that concerns about increased counterparty risk were focused on the lending side of the market.

In addition, Afonso, Kovner, and Schoar (2011) examine the behavior of the federal funds market throughout the 2007-2008 financial crisis, and the importance of liquidity hoarding and counterparty risk in the period after Lehman Brothers' bankruptcy. They find that large banks that borrow in the federal funds market experience a sharp increase in spreads and a drop in loan amounts on September 15, 2008, immediately following Lehman Brothers' bankruptcy, and that these effects are strongest for banks with higher levels of non-performing loans. This suggests that heightened concerns about counterparty risk increased the cost of liquidity and reduced access to it for weaker banks. They do not find evidence of liquidity hoarding in the overnight federal funds market.

Bech and Garratt (2012) also discuss how the Lehman Brothers bankruptcy caused changes in Fedwire payment patterns. Their theoretical model suggests that counterparty risk can lead to a delay in payments, as sending institutions have lower confidence that their funds will be

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returned later in the day. The model also suggests that excess liquidity can cause payments to shift to earlier in the day, by reducing the cost of that liquidity to market participants. Both of these characteristics were evidenced in the payment patterns that occurred right around the Lehman Brothers bankruptcy when counterparty credit concerns spiked and also in subsequent weeks when borrowing from the Federal Reserve liquidity facilities ballooned.

A number of other papers have analyzed interbank borrowing and lending during crises. Affinito (2012) and Pröpper, van Lelyveld, and Heijmans (2008) find that the network structure of Italian and Dutch interbank markets, respectively, is persistent and that it stayed largely intact during the 2007-2008 crisis. Using e-MID data to explore European interbank lending around the time of the crisis, Angelini, Nobili, and Picillo (2011) find that the elevated interest rate spread between secured and unsecured borrowing was driven by aggregate factors at the onset, but became more borrower-specific after August 2007. Additionally, large firms saw better borrowing conditions than small firms, suggesting that implied government guarantees may have softened counterparty risk for the big players in the market. Looking at liquidity demand of large settlement banks in the United Kingdom, Acharya and Merrouche (2012) also find that after August 2007 banks with high counterparty risk saw the largest increase in demand for liquidity. Days with high payment activity also experienced the largest increases in liquidity demand, suggesting that some liquidity hoarding was going on as well.

Afonso and Shin (2008) analyze the implication of liquidity hoarding in payment systems where each payment is large relative to the total stock of reserves. They find that liquidity hoarding can cause disruptions in such payment systems as well as in the whole financial system. Acharya and Skeie (2011) come to a similar conclusion by modelling the behavior of banks that find themselves with high levels of short-term leverage and high demand for precautionary liquidity. Others (Heider, Hoerova, and Holthausen (2010), Gale and Yorulmazer (2013)) point to heightened uncertainty, asymmetric information, and moral hazard as the theoretical causes of liquidity hoarding during crises. As in the crisis of 2007-2008, financial institutions short on liquidity might need to turn to fire sales of illiquid assets, justifying non-traditional central bank measures like large-scale asset purchases, stress tests, and interbank loan guarantees (Brunetti, Filippo, and Harris (2011), De Haan and van den End (2013), Acharya, Gromb, and Yorulmazer (2012)).

Our work builds on this literature by focusing on the federal funds market, putting the 2007-2008 crisis in the context of historical and post-crisis lending trends, and assessing the relative importance of counterparty and liquidity risk since the crisis. We find that the most fundamental changes in the federal funds market occurred several months after Lehman Brothers' bankruptcy. We go beyond the work by Afonso, Kovner, and Schoar (2011), for example, whose findings are largely based on the change in spreads observed the day after Lehman

Brothers filed for bankruptcy. It is unclear, however, what that change in spreads captures exactly, since it was mostly reversed the next day with the announcement of the bailout of AIG. Furthermore, loan amounts and spreads were so volatile that any signal based on a day's worth of data is likely to be too noisy for reliable inferences. In fact, major events like the terrorist attacks of September 11, 2001 and Lehman Brothers' bankruptcy are barely noticeable in the daily transactions data.

Unlike previous studies which classify banks as simply borrowers or lenders, our network metrics allow us to distinguish the large banks that make up the core of the market, from the smaller banks that either typically only lend to the core, or only borrow from the core. The banks in the core typically act as intermediaries and are engaged in both borrowing and lending, including to each other. These banks include the largest global banks, which were at the center of the financial crisis because of their exposures to the US housing market. The network approach allows us to better evaluate the relative importance of counterparty and liquidity risk because the banks in the core were most affected by these risks. This approach also allows us to document a dramatic and persistent restructuring of borrowing and lending patterns in the market from 1998 to 2012.

3   The Federal Funds Market and Fedwire Data

From the Volcker era through the beginning of the financial crisis, the Federal Open Market Committee (FOMC) implemented its monetary policy goals of maximum employment, stable prices, and moderate long-term interest rates primarily by affecting conditions in the federal funds market. For many years, the FOMC has employed a target for the interest rate at which depository institutions trade balances held at the Federal Reserve in the federal funds market; this rate is called the federal funds rate. The FOMC directs the Open Market Desk at the Federal Reserve Bank of New York to create conditions in the reserve market consistent with federal funds trading near the target.

Federal funds transactions are unsecured loans of balances at Federal Reserve Banks between depository institutions and certain other institutions, including government-sponsored enterprises.[1] A borrower is said to buy funds whereas a lender is said to sell funds. The vast majority of trades are spot and the duration is typically overnight, but forward trades and trades for longer terms (called term federal funds) also take place. Our results focus on overnight trading because this is where most of the trading in federal funds occurs.

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[1]More specifically, federal funds are deposit liabilities that are exempt from the reserve requirements under the Federal Reserve's Regulation D. They include deposits of a domestic office of another depository institution, agencies of the US government, Federal Home Loan Banks, and Edge Act or Agreement corporations.

In general, there are two methods for trading federal funds. Buyers and sellers can either arrange trades directly (typically using an existing relationship) or employ the services of federal funds brokers. Like other brokers, federal funds brokers do not take positions themselves. Rather, for a fee, they bring buyers and sellers together on an ex-ante anonymous basis. That is, the broker will inform the seller about the identity of the buyer only after the seller's offer has been accepted. The repeated nature of the interactions ensures that a seller accepts the trade regardless of the buyer unless the seller does not have a specific credit line to the buyer or the line is already maxed out (Stigum and Crescenzi (2007)). Based on summary reports from brokers, every morning the Federal Reserve Bank of New York publishes the dollar weighted average rate of brokered trades, known as the effective federal funds rate, for the previous business day.

Trades are generally settled by the Federal Reserve's Fedwire Funds Service (Fedwire) which allows account holders to transfer funds in real time until the regular close of the system at 6:30 p.m. (6:00 p.m. for non-bank financial institutions). Unlike other parts of the money market, such as the repo market, the federal funds market tends to stay active throughout the day; according to Bartolini, Hilton, and McAndrews (2010), about 40 percent of the trading occurs in the two hours before the close of Fedwire.

The federal funds market emerged in the 1920s as a method of adjusting reserve positions, but over time the market acquired increased importance as an outlet for short-term investments and as a marginal source of funding. The need for adjusting reserve positions arises from a combination of Federal Reserve regulations and the redistribution of balances that result from the daily flow of payments across accounts at the Federal Reserve. The Federal Reserve imposes penalties on account holders if they end a day overdrawn. In addition, depository institutions with reserve requirements (i.e., the amount of funds that they must hold in reserve against specified deposit liabilities) are penalized if they hold an insufficient level of balances (and vault cash) relative to their requirement at the end of each reserve maintenance period.

As described by Stigum and Crescenzi (2007), before the financial crisis, larger banks tended to be net buyers of federal funds, while smaller ones were often net sellers, because large corporate customers often borrowed funds from the former and individuals often deposited funds at the latter. Moreover, because of their business models, historically the Government-Sponsored Enterprises (GSEs) were large net sellers of funds. Fannie Mae and Freddie Mac, in particular, used the market as a short-term investment vehicle for incoming mortgage payments before passing the funds on in the form of principal and interest payments to investors. After the introduction of the conservatorship and related rules in 2008, however, GSE lending in the federal funds market dropped considerably, and for Fannie Mae and Freddie Mac, fell to zero in 2011. By contrast, Federal Home Loan Bank investments in the federal funds market

continued, as these institutions use the federal funds market to warehouse liquidity in order to meet unexpected borrowing demands from members.

For our calculations, we use proprietary transaction-level data from the Fedwire funds transfer service that has been matched to form plausible overnight funding transactions, likely related to the federal funds market. Similar data and matching algorithm were first used by Furfine (1999) and since then by a list of other authors, most often associated with the Federal Reserve Bank of New York. The transaction data set contains basic transfer information, including the amount of the transaction, the implied interest rate of the identified transaction, and the seller and buyer in the trade. These last two pieces of information allow us to differentiate the rates earned by depository institutions and GSEs in order to evaluate the empirical implications described above.

The algorithm matches an outgoing Fedwire funds transfer sent from one account and received by another, with a corresponding incoming transfer on the next business day sent by the previous day's receiver and received by the previous day's sender. This pair of transfers is considered a federal funds transaction if the amount of the incoming transfer is equal to the amount of the outgoing transfer plus interest at a rate consistent with the rates reported by major federal funds brokers. However, because we have no independent way to verify if these are actual federal funds transactions, our identified trades and characteristics of these trades are subject to error. In particular, one drawback of these data is that some portion of the transfers likely reflects Eurodollar transactions, which also go over Fedwire. Traditionally, Eurodollars traded at rates similar to federal funds, although there have been some periods post-crisis where the rates have diverged. Consequently, while we refer to these trades as federal funds volume, they are better characterized as identified overnight funding volume, and so should be used as a guide, and not an absolute figure, when discussing federal funds volume.[2] That said, our estimates are similar to those obtained using Call Report and other regulatory data.[3]

Figure 1 shows our daily estimates of federal funds volume by all Fedwire participants.[4] Federal funds volume gradually climbed from an average of roughly $100 billion per day in 1998, to almost $300 billion in June 2007. As shown by the shaded region in Figure 2, estimated federal funds volume was relatively stable around the $220 billion range even through the Bear Stearns (March 2008) and Lehman Brothers (September 2008) failures. Afonso, Kovner, and Schoar (2011) also find that the overnight federal funds market was "remarkably stable" during

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[2]Refer to Armantier and Copeland (2012).

[3]See for example Afonso, Entz, and LeSueur (2013).

[4]We exclude selected transactions between the large custodian banks in our analysis because at least a portion of them likely represent funding transactions other than for federal funds, which the algorithm fails to identify as different.

this period, as the amounts transacted, number of institutions participating in the market, and dollar-weighted average interest rate remain relatively unchanged. However, they show that large banks show reduced amounts of daily borrowing after Lehman Brothers' bankruptcy and borrow from fewer counterparties. Our analysis using network topology metrics shows further evidence that the federal funds market was increasingly stressed at this time. In October, financial markets (including the federal funds market) came under severe stress. At a conference call of the FOMC on October 7, 2008, former Federal Reserve Chairman Bernanke stated:

> "It's more than obvious that we have an extraordinary situation. It is not a single market. It's not like the 1987 stock market crash or the 1970 commercial paper crisis. Virtually all the markets–particularly the credit markets–are not functioning or are in extreme stress. It's really an extraordinary situation, and I think everyone can agree that its creating enormous risks for the global economy." – Board of Governors of the Federal Reserve System (2008a)

In the same call, FOMC member Donald Kohn stated

> "This is a credit crunch. Banks won't lend to each other." – Board of Governors of the Federal Reserve System (2008a)

The Federal Reserve's Greenbook report prepared for the October 28-29 FOMC meeting also noted that

> "overnight federal funds traded within an unusually wide range, reflecting tiering across institutions." – Board of Governors of the Federal Reserve System (2008b)

Federal funds volume dropped dramatically during the first half of December 2008, a few months after the Federal Reserve began to pay interest on reserves. A few factors likely explain at least some of this dramatic drop-off. First, reserve balances continued to climb through the fall of 2008 and were expected to increase even further with the announcement of the first round of large-scale asset purchases in November 2008. A system awash in liquidity likely did not need as much marginal borrowing to cover account positions. Second, the advent of interest on reserve balances in October 2008 also lowered the cost of keeping excess reserve balances on account at the Federal Reserve. Third, on December 16, 2008, the target federal funds rate was lowered to its effective zero lower bound, decreasing the incentive to engage in reserve market arbitrage at an absolute level. And finally, as evidenced by the surge in average CDS spreads of U.S. banks in the fall of 2008 shown in Figure 3, counterparty credit concerns soared in the wake of the Lehman Brothers episode and remained elevated for some

time. As we explore later in the paper, the increase in counterparty risk was associated with a reduction in both the number of loans and amount lent on credit lines to individual institutions. For example, the Federal Reserve's Bluebook prepared for the December FOMC meeting stated that "many sellers [of federal funds] reportedly tightened their counterparty credit limits."(Board of Governors of the Federal Reserve System (2008c)) Following the fall of 2008, federal funds volume hovered around the $150 billion range until mid 2011, after which it continued to decline, eventually stabilizing at $110 billion by year-end 2012, or 40 percent of its level in mid 2007.[5]

4   Federal funds market from a network perspective

We rely on network theory to analyze the various patterns of connections in the federal funds market. In our context, the federal funds network describes a collection of nodes (banks), and the links (federal funds transactions) between them. We model federal funds flows as a directed network linking the sender of the payment (lender) to the receiver of the payment (borrower). We adopt a similar set of statistical measures of the network's topology as in Soramaki, Bech, Arnold, Glass, and Beyeler (2006) to characterize how the network evolved on a daily basis over a 15-year period from 1998 to 2012, paying special attention to the 2007-2008 financial crisis.

Figure 4 shows that there was a sharp contraction in the number of links in the network during the last quarter of 2008, as fewer banks were transacting with each other. As shown in Figure 5, the number of links appears to negatively related to the average CDS spread of major U.S. banks (the correlation between the two series is -0.59 at the daily frequency), suggesting that increases in counterparty risk may make banks more reluctant to lend to each other. Also, the red line Figure 4 shows a sizable increase in the average dollar volume transacted per link, which, as we demonstrate later, is largely driven by the exit of many of the smaller banks from the market. With these in mind, Figure 6 shows one measure of connectedness, the degree of completeness, defined as the number of links over the number of possible links. For a directed network, the degree of completeness is given by $\alpha = \frac{m}{n(n-1)}$, where m is the number of links and n is the number of nodes. Interestingly, the federal funds network started becoming more complete starting in late 2008. Although the reduction in links in late 2008 would have made the network less complete, the reduction in the number of participants (nodes) in the network resulted in an even larger reduction in the number of possible links.

To understand better what factors caused these changes in the network topology, we first

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[5]In contrast, overall Fedwire payments volume dropped by only 3 percent between mid-2007 and end-2012.

group the nodes into components based on how they interact with other nodes on any given day. Banks may switch groups from day to day, depending on their borrowing and lending relationships with other banks. Figure 7 illustrates the components of our network. The GSCC component is defined as the largest set of nodes that can reach each other via directed paths (Jackson (2010)). For example, if bank A lends to bank B, and bank B lends to bank C, then one can trace a directed path from bank A to bank C. Hereafter, we refer to the GSCC group as "the core" of the network. The banks in the core are engaged in both borrowing and lending, amongst each other and with banks in the GIN and GOUT groups. Banks (and other nonbank entities with Federal Reserve accounts, such as the GSEs) in the GIN group have directed paths to the core but not from it. That is, they lend federal funds to the core, but they do not borrow from the core. The opposite is true for banks in the GOUT group: they borrow from the core but do not lend to it. Tendrils are in the "suburbs" of the network because they have no directed paths to the core– they typically either borrow from GIN, lend to GOUT, or both. The GWCC is simply the union of the GIN, core, GOUT, and tendrils. The few nodes which are outside the GWCC, but which connect to each other via undirected paths, are the disconnected components (DCs). We mostly ignore them because they represent a negligible fraction of the overall federal funds transaction volume.

To illustrate how the federal funds network can change, Figure 8 shows the federal funds network on the day before the terrorist attacks of September 11, 2001 (left panel), on the day of the attack (middle panel), and on the following Monday (right panel). On September 10, there were over 400 institutions lending or borrowing in the federal funds market, with over half of them in the GIN component. The core of the network was comprised of 25 banks. On September 11, the network shrunk by more than half its size the previous day, with less than 20 lenders in the GIN group, and just a few banks in the core. Likely because of the infrastructure destruction in lower Manhattan, banks were unable to connect to the Fedwire network as usual, and so the connectedness of the network fell dramatically. Importantly, there was a complete recovery of the network by the following Monday (right panel).[6]

For markedly different reasons than on September 11, a similar hollowing out of the network occurred in the fall of 2008. The change was much more gradual, as information about the shock to credit quality became clearer over a longer period. For example, as shown in the left panel of Figure 9, the federal funds network looked fairly normal on September 15, 2008, the day Lehman Brothers filed for bankruptcy. But the size of the network began to steadily decline thereafter, such that, by December of 2008, there were considerably fewer nodes and links (right panel). During this transition period, the structure of the federal funds network

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[6]Refer to Ferguson (2003) and Lacker (2004) for a more complete discussion of the effect of September 11 on the Federal Reserve and the U.S. payments system.

changed dramatically from day to day, as can be seen by Figure 14 in the Appendix, which is an animated version of the network plot.

Figure 10 shows the quarterly averages of the shares of daily dollar volume between the key components in the network. Between mid-2007 and the end of 2009, the core of the network diminishes in importance as lenders in the GIN component begin to lend directly either to banks in the GOUT component or to banks in the tendrils, bypassing the core. Also, lending between banks in the core group declines considerably. Figure 11 shows the evolution of the size (number of banks or nodes) of the various components of the federal funds network. The number of nodes gradually declined from its level in early 1998 to about half that level in 2004, reflecting, in part, the consolidation of the banking industry. The GIN is the largest component. Figure 12 focuses on the crisis period. Between June 2007 and August 2008, the network size shrunk by 13 percent, and the size of the GIN component shrunk by about a quarter. In the last two weeks of September 2008, just after Lehman Brothers filed for bankruptcy, the GIN component contracted another 20 percent. The network contracted further throughout the fall of 2008, after reserve balances began to rise and the Federal Reserve began to pay interest on reserves. By the end of 2008, the GIN was roughly one fourth of its size before the crisis, and over half of the participating institutions had dropped out of the market.

For the 591 institutions that participated in the federal funds market in 2008:Q3, Table 1 shows the transition in their predominant network component status between 2008:Q3 and 2009:Q2. If a bank does not participate at all in the federal funds network (no lending or borrowing activity) on a given day, it is assigned to the "absent" group that day. For each institution, we then count the number of days in each group to determine the predominant group. Of the 239 institutions that were predominantly in either the GIN, core, or GOUT components in 2008:Q3, 148 (62 percent) either dropped out entirely from the federal funds market (were in the "absent" group every day) or became "mostly absent" (were in the "absent" group more than in any other group) in 2009:Q2. The "mostly absent" row shows that in 2008:Q3 nearly half of the institutions were participating in the federal funds market only sporadically. On average, these institutions participated in the market only 11 out of the 64 days in the quarter, typically as small lenders in the GIN or tendrils components. However, by 2009:Q2, nearly three-quarters of these small sporadic lenders completely dropped out of the network. The large reduction in nodes from this category, however, only reduced overall federal funds transaction volume by less than one percent. For those lenders that remained predominantly in the GIN group, we also find that they participated less frequently in the market– on average they lent 43 out of 64 days in 2009:Q2, compared with 57 out of 64 days in 2008:Q3.

The banks that remained active in the federal funds market after the fall of 2008 reduced their lending volumes significantly. Table 2 compares the frequency distribution of the total dollar volume lent in 2008:Q3 and 2009:Q2. The distribution of lending volumes is highly concentrated amongst the largest banks – the small lenders which make up the vast majority of banks (i.e. those that lent less than $20 billion during all of 2008:Q3) account for just 5 percent of the total federal funds volume transacted during the period, whereas the largest lenders (i.e. those that lent over $500 billion in 2008:Q3) account for roughly half of the total volume. The drastic reduction in overall lending volume was mostly due to the largest banks reducing their credit lines. For example, over half of the banks that lent over $100 billion in 2008:Q3 reduced their lending volumes significantly in 2009:Q2. In sum, although many small sporadic lenders in the GIN component exited the market in the fall of 2008, the contraction in overall lending volume was mainly due to a reduction of credit lines by the largest lenders.

5 The role of counterparty and liquidity risk

How do counterparty and liquidity risk affect the dynamics of the federal funds network? First, we caution that it is impossible to completely disentangle these two risks from each other, which is especially true for the 2008 financial crisis. During the crisis, uncertainty surrounding the quality of assets on banks' balance sheets, especially those exposed to the U.S. subprime mortgage sector, made banks more reluctant to lend to each other. The resulting instability in interbank funding markets, in turn, made it more likely that a bank would lose access to funding and consequently default on its financial obligations (as happened with Lehman Brothers). This increase in the probability of default would again make banks more hesitant to lend to each other, reinforcing the cycle.

To break this cycle, the Federal Reserve took extraordinary actions to ensure that banks and other financial institutions had adequate access to short-term credit. For example, it acted as a lender of last resort to banks and other depository institutions by creating several new facilities that complemented the traditional discount window, such as the Term Auction Facility (or TAF, launched in December 2007), Primary Dealer Credit Facility (or PDCF, launched in March 2008), and the Term Securities Lending Facility (or TSLF, launched in March 2008).[7] In the fall of 2008, it also provided liquidity to borrowers and investors in key credit markets with programs such as the Commercial Paper Funding Facility (CPFF), Asset-Backed Commercial Paper Money Market Mutual Fund Liquidity Facility (AMLF), Money Market Investor Funding Facility (MMIFF), and the Term Asset-Backed Securities

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[7]For more information about the Federal Reserve's actions during the 2007-2008 financial crisis see `http://www.federalreserve.gov/monetarypolicy/bst_crisisresponse.htm`.

Loan Facility (TALF). As stated in a speech by former Federal Reserve Chairman Bernanke,

> "Liquidity provision by the central bank reduces systemic risk by assuring market participants that, should short-term investors begin to lose confidence, financial institutions will be able to meet the resulting demands for cash without resorting to potentially destabilizing fire sales of assets. Moreover, backstopping the liquidity needs of financial institutions reduces funding stresses and, all else equal, should increase the willingness of those institutions to lend and make markets." (Bernanke, 2009)

Our definition of "liquidity risk" is broad enough to encompass risks to both sides of a bank's balance sheet. On the liability side, it captures the risk that banks may be unable to roll over or replace maturing short-term funding transactions (e.g. repurchase agreements, commercial paper). On the asset side, it captures uncertainty about unexpected funding short-falls when assets under-perform (e.g. a rise in loan defaults or delinquencies), or losses when assets are sold at distressed prices. The Federal Reserve facilities described above allowed banks to replace increasingly volatile short-term funding sources with a secure source of funding from the Federal Reserve, which acted as lender of last resort. So the extent to which banks relied on these liquidity facilities during the crisis can be used as a proxy for the overall level of liquidity risk in the U.S. financial system. And moreover, as will be illustrated later, there can be some substitution from private lending and borrowing for liquidity purposes to Fed borrowing. In order to gauge the level of liquidity risk and the substitution between Fed borrowing and private borrowing, we use the amounts borrowed from the following facilities to gauge overall liquidity risk: Term Auction Facility, Primary Dealer Credit Facility, Commercial Paper Funding Facility, Asset-Backed Commercial Paper Money Market Mutual Fund Liquidity Facility, and the Primary Credit Facility.[8]

Because federal funds loans are unsecured, lenders typically evaluate the credit quality of potential borrowers to establish a maximum credit line for each one. When establishing credit lines for their counterparties, banks take into account the probability that the borrower will default on the repayment of a loan. To measure counterparty risk, we average the probabilities of default for some of the largest U.S. banks derived from premiums on credit default swaps (CDS), which are derivative contracts used by holders of corporate debt (and other investors) to insure against the event of bankruptcy or default. Specifically, we use the average of the spread on the 5-year CDS contract for selected large domestic banks that had liquid CDS contracts for the entire sample period, namely Citibank, J.P. Morgan, Wells Fargo, Capital One, and U.S.

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[8]These data can be found at: `http://www.federalreserve.gov/monetarypolicy/bst.htm`.

Bancorp.[9] The CDS quotes are from Markit Credit Default Swaps (CDS). Williams and Taylor (2009) find evidence that, between August 2007 and March 2008, increased counterparty risk between banks contributed to the jump in the spread between the 3-month LIBOR rate (the rate at which banks lend to each other on an unsecured basis for 3 months) and the overnight interest swap (OIS) rate. However, as noted by some members of the FOMC, in the wake of Lehman Brothers' bankruptcy there was very little term funding going on, so posted LIBOR rates did not necessarily reflect the banks' funding costs, making this spread a less reliable indicator of the funding strains they faced (Board of Governors of the Federal Reserve System (2008a)). Instead, we focus on quantity measures, such as overall activity in the federal funds market, and examine the effects of counterparty risk (proxied by CDS spreads) and liquidity risk (proxied by borrowings from the Federal Reserve's emergency liquidity facilities).

We adopt a general-to-specific model selection strategy that begins with a 'general unrestricted model' (GUM) that encompasses the essential characteristics of the underlying data.[10] We then seek to reduce its complexity by eliminating variables that are statistically insignificant to arrive at a parsimonious model that is nested in the initial GUM.[11] We search for the parsimonious and congruent model using *Autometrics*, which is part of the software package *PcGive/OxMetrics* (Doornik (2009), and Hendry and Doornik (2009)). *Autometrics* uses a tree-search algorithm to detect and eliminate statistically-insignificant variables, avoiding path-dependence. At any stage, a variable is only removed if the new model encompasses the GUM at the chosen significance level α (we set $\alpha = 0.01$). With *Autometrics*, some irrelevant variables may be retained because their deletion would make a diagnostic test (i.e. for autocorrelation, heteroscedasticity, and non-normality) significant, or because it may be jointly significant with other retained variables. When no variable meets the reduction criteria, a path along the tree is terminated. If there are multiple terminal models (all congruent, undominated, and mutually-encompassing representations of the GUM), the Schwarz (1978) information criterion is used to select the final model (Castle, Doornik, and Hendry (2011)). The terminal model is, by design, a statistically well-specified valid reduction of the GUM (Doornik (2008)). As a final check we examine the null hypotheses that the residuals of the terminal model are non-autocorrelated, homoscedastic, and Gaussian.

Our GUM includes changes in excess reserve balances (excluding the amounts borrowed from the Federal Reserve liquidity facilities) to control for changes in the supply of liquidity

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[9]Chen, Fleming, Jackson, Li, and Sarkar (2011) find that trading in the CDS market is concentrated in the 5-year tenor.

[10]The desired properties of the GUM, which make it congruent, are discussed in Hendry (1995).

[11]This approach is also known as the 'LSE' method closely associated with David Hendry (Hendry (1995)). Campos, Ericsson, and Hendry (2005) provide a good overview of general-to-specific modelling. See also Ericsson (2010) and Ericsson and Kamin (2009) for applications using Autometrics.

in the market. Banks began to accumulate large amounts of excess reserve balances after the Federal Reserve stopped offsetting increases in credit and lending by shedding other assets in the fall of 2008. Excess reserve balances continued to climb through a series of large-scale asset purchase programs, which prompted increases in reserve balances early in 2009 and through the end of our sample in 2012. The GUM also allows for other factors that could affect activity in the federal funds market such as the spread between the effective federal funds rate and the target federal funds rate, trading volume in S&P500 stocks, and payments volume in the Fedwire system (excluding federal funds transactions identified by our algorithm), which are a proxy for payment shocks. The GUM also includes time dummies for known calendar effects in the federal funds market: maintenance period day, FOMC announcement day, day before and after a holiday, the first and last day of each month, end of quarter, and end of year. The GUM also includes 5 lags of all the variables (except the time dummies).[12]

Daily financial data are quite noisy and despite our attempts to control for known calendar effects, it is important to ensure that our estimates are robust to the presence of outliers. To this end, we perform block additions of impulse dummies for all observations using a method known as impulse indicator saturation (IIS), which is implemented as an option in *Autometrics*. Recent developments in this field include Santos, Hendry, and Johansen (2008) and Johansen and Nielsen (2009). When using *Autometrics*, we 'force' some variables to be unrestricted, meaning that they will always be retained. The unrestricted variables are the constant, and the contemporaneous (lag-0) measures of economic variables we care about: CDS spreads, borrowings from the Federal Reserve's emergency liquidity facilities, changes in excess reserve balances, the spread between the effective federal funds rate and the target federal funds rate, trading volume in the S&P500 stocks, and payments volume in the Fedwire system. After selecting the final model, we obtain the static long-run solution to the dynamic OLS equation and report the coefficients. All standard errors are robust to any remaining heteroscedasticity and autocorrelation present in the residuals.

We split our sample into 3 time periods: pre-crisis (from 8/2/2004 - 5/31/2007), early crisis (6/1/2007 - 9/30/2008), and late crisis (1/2/2009 - 8/31/2012).[13] We intentionally exclude the fourth quarter of 2008 – the turbulent period after Lehman Brothers' bankruptcy, because during this period federal funds volume is plummeting and most of our network metrics are transitioning to a new level. Although including this transition period in our regressions would

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[12]We chose 5 lags because the data are measured on business days.

[13]We also ran regressions using the full sample period and including a dummy variable for the period following Lehman Brothers' bankruptcy, which we then interacted with our measures of counterparty and liquidity risk. The estimated effects are very similar to those we obtain by splitting the sample. We report the split-sample results because the residuals of the full-sample regressions are plagued by autocorrelation, heteroscedasticity, and non-normality.

strengthen the statistical significance of our results, empirical tests suggest that doing so would introduce irregularities such as autocorrelation, heteroscedasticity, and non-normality in the residuals. In addition, there was a significant structural change in reserves administration between our second subsample and the third. Specifically, the Federal Reserve started to pay interest on excess reserves (IOER) on October 8, 2008. The differences in the constant in each regression can demonstrate the baseline effect of this regime change in each sample period.

Table 3 shows regression estimates for total federal funds dollar volume as identified by our Fedwire data.[14] The coefficient on the 5-year CDS spread (our proxy for counterparty risk) is negative in the pre-crisis and early crisis periods, but not statistically significant. In the late crisis period (after Lehman Brothers' bankruptcy) it becomes more negative and highly significant (at the $\alpha = 0.001$ level). The coefficient for the change in the Federal Reserve liquidity facilities (our proxy for liquidity risk) is also only negative and significant in the late crisis period. These results suggest that liquidity and counterparty risk only began to significantly affect the aggregate volume of federal funds transactions later in the crisis, after the bankruptcy of Lehman Brothers. The estimated coefficient on the change in Fed liquidity facilities is greater than 1 in absolute value in the late crisis period, which implies that our proxy for liquidity risk is capturing more than just a pure substitution effect to federal funds loans from a more stable source of funding from the Federal Reserve. The negative coefficient is suggestive that as institutions depended less on Fed liquidity, they were more likely to borrow from one another. As expected, we find that payment shocks (non-federal funds Fedwire payments), and trading volume in S&P500 stocks are positively related to lending activity in the federal funds market, especially in the late crisis period. We are surprised to find a positive coefficient on the change in excess reserve balances in the late crisis period, suggesting that changes in the supply of liquidity in the market are *positively* associated with increases in federal funds transactions. One possible explanation for this is that increases in excess reserves were immediately redistributed to banks that had the greatest incentive to hold them. Such institutions might include U.S. branches of European banks who, unlike US-chartered banks, were not affected by a new Federal Deposit Insurance Corporation charge on wholesale funding (McCauley and McGuire (2014)). This view is supported by the fact that foreign-related commercial banks in the United States dramatically increased their holdings of Federal Reserve balances and other cash assets during this period, both in dollar terms (Figure 13, left panel) and as a share of their assets (Figure 13, right panel). The negative coefficient on the change in Fed liquidity facilities suggests that as banks demanded Fed liquidity, the

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[14]The p-values for the residual tests reported at the bottom of the table show that, in most cases, we fail to reject the null hypotheses (at $\alpha = 0.05$) that the residuals are non-autocorrelated, homoscedastic, and Gaussian.

demand for private liquidity fell; likewise, as the demand for Fed liquidity dropped, private liquidity increased. This result suggests that to some extent, Fed liquidity was a substitute for private liquidity, particularly during the acute phases of the financial crisis. The constant indicates that all else equal, federal funds volume dropped with the advent of IOER, and likely as well with the sharp increase in reserve balances that was concurrent with that change.

Table 4 focuses on lending from the GIN component to the core of the network. In contrast to the regressions for federal funds dollar volume, the coefficients on the 5-year CDS spread are negative and significant even in the early-crisis period. That is, even though overall federal funds lending did not contract much in the early phase of the financial crisis (June 2007 to September 2008), the small lenders in the GIN component began to reduce lending to the core as counterparty risk increased. This coefficient becomes more negative and significant in the late crisis period. However, we do not find evidence that liquidity risk significantly affected lending volumes from GIN to the core. IOER put downward pressure on lending, but not to a great extent.

Table 5 shows regressions for the size of the GIN component, that is, the number of institutions that lend to the core. The coefficient on CDS spreads is negative and significant in the early crisis period, which suggests that even before Lehman Brothers' bankruptcy, some lenders were factoring in counterparty risk when deciding whether or not to lend to the core. In the late crisis period the CDS spread is not a significant determinant for the size of the GIN component, perhaps because most lenders had already exited the market. The size of the GIN component is negatively related to our proxy for liquidity risk in the late crisis period, which indicates that there were even fewer banks lending to the core on days when borrowing from the Federal Reserve liquidity facilities was high. Table 6 examines how lending within the core of the network responds to changes in counterparty and liquidity risk. The coefficient on the CDS spread is negative and statistically significant only in the late crisis period, suggesting that the largest banks in the core of the network became more reluctant to transact with each other when their perceived counterparty risks reached unprecedented levels. Liquidity risk, on the other hand, appears to affect lending activity within the core in both periods.

In sum, the results in Tables 3-6 suggest that both counterparty and liquidity risk began to significantly alter lending patterns in the federal funds network starting in the early crisis period, but these effects became stronger in the late crisis period. In the early crisis period, our results indicate that counterparty risk was associated with decreased lending from GIN to the core, and with fewer lenders in the GIN component. During the same period, we find that liquidity risk was also negatively associated with lending within the core. In the late crisis period, the negative relationships between counterparty risk, liquidity risk, and overall federal funds transaction volume became stronger and highly statistically significant.

During this period, we also find evidence that lending within the core became more sensitive to counterparty risk.

6   Panel regressions using bank-level data

Although the results of the previous section suggest a strong relationship between counterparty risk, liquidity risk, and lending in the federal funds market after the fall of 2008, more evidence is needed to infer any causality. In this section we perform panel regressions using bank-level data for banks that are in the core of the network to explore how their borrowing and lending is influenced by their own counterparty and liquidity risk. Our bank-specific measure of counterparty risk is again the (log) CDS spread. Because of CDS price data availability, we include only 10 banks in our panel.[15] Our proxy for bank-specific liquidity risk is the change in borrowing from the Federal Reserve's Term Auction Facility (TAF), available to depository institutions from December 20, 2007 to April 8, 2010. We also control for bank-specific changes in reserve balances.

Table 7 shows panel regression results on the log of dollar volume borrowed from lenders in the GIN component. In the late crisis period, the negative and statistically significant (at $\alpha = 0.001$) coefficient on the log CDS spread suggests that banks in the core who were less creditworthy borrowed less from lenders in the GIN component. Table 8 examines dollar volume borrowed from other banks in the core (core to core lending). Although the coefficient on the log CDS spread is negative in both the early and late crisis periods, it is not statistically significant. However, in the late crisis period we do find a negative and statistically significant coefficient on the change in TAF borrowing. This indicates that banks that relied more heavily on the Federal Reserve's TAF facilities borrowed less from their peers in the core of the network, supporting the view that heightened liquidity risk may have contributed to reduced reliance on the federal funds market.

Table 9 shows panel regression results for the number of lending institutions in the GIN component from which banks in the core borrow. As we saw in Table 5, the coefficient in the CDS spread becomes negative and highly significant starting in the early crisis period. It remains negative, but smaller in magnitude, in the late crisis period. These results indicate that fewer institutions were willing to lend to banks in the core when these banks became less creditworthy. It also provides evidence supporting the view that the mass exodus of GIN lenders from the federal funds market in the fall of 2008 was at least in part due to the rapid increase in counterparty risk during that period. Table 10 shows a similar set of results for

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[15]These 10 banks, all frequent members of the core, are some of the largest financial institutions.

the number of banks in the core that lend to other banks in the core. Again, we find that counterparty risk was a negative influence on lending in the early phase of the crisis and liquidity risk a negative influence in the late phase of the crisis.

7   Conclusion

Our work builds upon the existing literature on interbank lending by closely examining how changes in counterparty and liquidity risk alter the dynamics of the federal funds network. Our network approach allows us to distinguish large banks that make up the core of the network from smaller ones that either typically only lend to the core or only borrow from the core. Because banks in the core of the network include the largest global banks which were at the center of the financial 2007-2008 crisis, their interactions amongst themselves and with other parts of the network allow us to better evaluate the relative importance of counterparty and liquidity risk. Our network measures also show the dramatic restructuring of borrowing and lending patterns in the market from 1998 to 2012, and provide further evidence that the federal funds market became increasingly stressed starting in mid-2007.

In the early phase of the crisis, the number of lenders lending to the core shrunk by roughly a quarter. Our analysis suggests that these lenders began cutting credit lines to banks in the core as counterparty risk increased. Lenders in the GIN component began lending directly to borrowers in the GOUT component, bypassing the intermediaries in the core. The banks in the core, in turn, transacted less with each other, and became increasingly reliant on funding from the Federal Reserve's liquidity facilities. Thus, the Federal Reserve's liquidity facilities appear to have served as a substitute for the federal funds market (and likely other sources of short-term funding too), which indicates that banks, particularly those in the core, were trying to mitigate liquidity risk by securing more stable sources of funding. In the late crisis period (after Lehman Brothers' bankruptcy), the amounts lent by banks that were still left in the GIN component became increasingly tied to the perceived counterparty risk of the core, and the network became even more sensitive to heightened levels of counterparty and liquidity risk.

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Tables

Frequency	2009:Q2				
Row percent	DC or Tendrils	GIN, GOUT, or GSCC	Mostly absent	Dropped out	Total
2008:Q3					
Mostly absent	**4**	**3**	**74**	**210**	**291**
	1	*1*	*25*	*72*	
DC or Tendrils	**13**	**4**	**25**	**19**	**61**
	21	*7*	*41*	*31*	
GIN, GOUT, or GSCC	**34**	**57**	**63**	**85**	**239**
	14	*24*	*26*	*36*	
Total	**51**	**64**	**162**	**314**	**591**

Table 1: **Transition matrix of network component status between 2008:Q3 and 2009:Q2.** For the 591 institutions that participated in the federal funds market in 2008:Q3, this table shows the conditional frequency distribution of the network components they mostly belonged to in 2008:Q3 and 2009:Q2. DC = disconnected components. GIN = Giant-In Component. GOUT = Giant-Out Component. GSCC = Giant Strongly Connected Component (core). "Mostly absent" denotes institutions that, for the most part, did not transact in the federal funds market during the quarter. The "dropped out" column for 2009:Q2 denotes institutions that did some lending or borrowing in 2008:Q3, but had no transactions in 2009:Q2. Row percents may not add to 100 due to rounding.

Frequency	2009:Q2 (billions of dollars)				
Row percent	⩽$20	($20-$100)	[$100-$500)	⩾$500	Total
2008:Q3					
⩽$20	**523**	**0**	**0**	**0**	**523**
	100	*0*	*0*	*0*	
($20-$100)	**26**	**15**	**0**	**0**	**41**
	63	*37*	*0*	*0*	
[$100-$500)	**8**	**4**	**9**	**0**	**21**
	38	*19*	*43*	*0*	
⩾ $500	**0**	**0**	**3**	**3**	**6**
	0	*0*	*50*	*50*	
Total	**557**	**19**	**12**	**3**	**591**

Table 2: **Transition matrix of lending volumes, 2008:Q3 and 2009:Q2.** For the 591 institutions that participated in the federal funds market in 2008:Q3, this table shows the conditional frequency distribution of the total dollar volume lent in 2008:Q3 and 2009:Q2. Row and column headings denote lending intervals in billions of dollars. Row percents may not add to 100 due to rounding.

	Pre crisis: 8/2/04 - 5/31/07		Early crisis: 6/1/07 - 9/30/08		Late crisis: 1/2/09 - 8/31/12	
Constant	23.46		281.19	**	103.07	**
	(0.24)		(2.64)		(2.73)	
Log CDS spread	-11.24		-4.04		-22.91	***
	(-1.20)		(-0.59)		(-3.73)	
Log fedwire payments	90.60	***	26.25		50.59	***
	(4.19)		(0.65)		(3.41)	
Change in excess reserve balances	0.14		-0.36		0.66	***
	(0.24)		(-1.32)		(6.26)	
Federal funds rate (effective-target)	19.41		56.30	*	131.25	**
	(0.42)		(2.27)		(2.93)	
Log S&P500 volume	25.22	*	-6.54		16.59	***
	(2.47)		(-0.49)		(6.07)	
Change in fed liquidity facilities			-0.06		-1.34	**
			(-0.11)		(-3.07)	
N. impulse dummies	30		12		42	
N. observations	713		336		923	
Adj. R-squared	0.80		0.66		0.83	
Autocorr. test (p-value):	0.07		0.61		0.25	
ARCH test (p-value):	0.81		0.81		0.89	
Normality test (p-value):	0.48		0.33		0.18	

Table 3: **Regressions for federal funds dollar volume.** Coefficients are for the solved static long-run equation. Robust t-statistics in parentheses. *** denotes significance at $\alpha = 0.001$, ** at $\alpha = 0.01$, and * at $\alpha = 0.05$. The dependent variable is estimated federal funds volume expressed in billions of dollars. Estimation begins with a general unrestricted model which includes a constant, 5 lags of the dependent variable, 5 lags of each of the explanatory variables shown in the table, and time dummies for maintenance period day, day before holiday, day after holiday, last day of month, last day of quarter, last day of year, and FOMC announcement day. Model selection is performed using *Autometrics* (Hendry and Doornik (2009)), and only a subset of the retained regressors are shown. Fedwire payments volume excludes identified federal funds transactions. 5-year CDS spread is average of CDS spreads of Citibank, J.P. Morgan, Wells Fargo, Capital One, and U.S. Bancorp. Federal reserve liquidity facilities are the outstanding balance on the Term Auction Facility, Primary Dealer Credit Facility, Commercial Paper Funding Facility, Asset-Backed Commercial Paper Money Market Mutual Fund Liquidity Facility, and the Primary Credit Facility.

	Pre crisis: 8/2/04 - 5/31/07		Early crisis: 6/1/07 - 9/30/08		Late crisis: 1/2/09 - 8/31/12	
Constant	-52.55		121.99	*	104.63	***
	(-0.78)		(2.34)		(7.17)	
Log CDS spread	-9.01		-13.42	***	-17.79	***
	(-1.43)		(-4.98)		(-7.57)	
Log fedwire payments	67.28	***	53.81	***	13.45	*
	(5.49)		(4.44)		(2.49)	
Change in excess reserve balances	0.62		0.03		0.14	***
	(1.62)		(0.31)		(4.81)	
Federal funds rate (effective-target)	-41.24		0.76		25.06	
	(-1.57)		(0.07)		(1.5)	
Log S&P500 volume	19.54	**	0.32		3.04	**
	(2.75)		(0.05)		(2.83)	
Change in fed liquidity facilities			-0.44		-0.21	
			(-1.87)		(-1.36)	
N. impulse dummies	15		9		35	
N. observations	713		336		923	
Adj. R-squared	0.62		0.51		0.64	
Autocorr. test (p-value):	0.11		0.58		0.51	
ARCH test (p-value):	0.06		0.22		0.64	
Normality test (p-value):	0.28		0.79		0.49	

Table 4: **Regressions for GIN lending to core.** Coefficients are for the solved static long-run equation. Robust t-statistics in parentheses. *** denotes significance at $\alpha = 0.001$, ** at $\alpha = 0.01$, and * at $\alpha = 0.05$. The dependent variable is estimated federal funds loans from GIN to core expressed in billions of dollars. Estimation begins with a general unrestricted model which includes a constant, 5 lags of the dependent variable, 5 lags of each of the explanatory variables shown in the table, and time dummies for maintenance period day, day before holiday, day after holiday, last day of month, last day of quarter, last day of year, and FOMC announcement day. Model selection is performed using *Autometrics* (Hendry and Doornik (2009)), and only a subset of the retained regressors are shown. Fedwire payments volume excludes identified federal funds transactions. 5-year CDS spread is average of CDS spreads of Citibank, J.P. Morgan, Wells Fargo, Capital One, and U.S. Bancorp. Federal reserve liquidity facilities are the outstanding balance on the Term Auction Facility, Primary Dealer Credit Facility, Commercial Paper Funding Facility, Asset-Backed Commercial Paper Money Market Mutual Fund Liquidity Facility, and the Primary Credit Facility.

	Pre crisis: 8/2/04 - 5/31/07		Early crisis: 6/1/07 - 9/30/08		Late crisis: 1/2/09 - 8/31/12	
Constant	67.06		586.43	***	18.22	
	(0.73)		(6.43)		(0.78)	
Log CDS spread	12.04		-13.94	**	-2.19	
	(1.32)		(-2.97)		(-0.58)	
Log fedwire payments	109.38	***	-8.17		-14.39	
	(4.71)		(-0.38)		(-1.33)	
Change in excess reserve balances	13.46	***	-0.76	**	0.04	
	(4.98)		(-2.62)		(0.87)	
Federal funds rate (effective-target)	-2.33		35.82	*	112.68	***
	(-0.05)		(2.16)		(4.45)	
Log S&P500 volume	4.14		-39.61	***	7.63	***
	(0.42)		(-3.4)		(4.58)	
Change in fed liquidity facilities			-0.17		-2.11	***
			(-0.44)		(-4.98)	
N. impulse dummies	15		9		54	
N. observations	713		336		923	
Adj. R-squared	0.45		0.73		0.92	
Autocorr. test (p-value):	0.02	*	0.24		0.29	
ARCH test (p-value):	0.76		0.54		0.05	
Normality test (p-value):	0.38		0.71		0.58	

Table 5: **Regressions for size of GIN component.** Coefficients are for the solved static long-run equation. Robust t-statistics in parentheses. *** denotes significance at $\alpha = 0.001$, ** at $\alpha = 0.01$, and * at $\alpha = 0.05$. The dependent variable is the number of nodes (institutions) in the GIN component. Estimation begins with a general unrestricted model which includes a constant, 5 lags of the dependent variable, 5 lags of each of the explanatory variables shown in the table, and time dummies for maintenance period day, day before holiday, day after holiday, last day of month, last day of quarter, last day of year, and FOMC announcement day. Model selection is performed using *Autometrics* (Hendry and Doornik (2009)), and only a subset of the retained regressors are shown. Fedwire payments volume excludes identified federal funds transactions. 5-year CDS spread is average of CDS spreads of Citibank, J.P. Morgan, Wells Fargo, Capital One, and U.S. Bancorp. Federal reserve liquidity facilities are the outstanding balance on the Term Auction Facility, Primary Dealer Credit Facility, Commercial Paper Funding Facility, Asset-Backed Commercial Paper Money Market Mutual Fund Liquidity Facility, and the Primary Credit Facility.

	Pre crisis: 8/2/04 - 5/31/07		Early crisis: 6/1/07 - 9/30/08		Late crisis: 1/2/09 - 8/31/12	
Constant	51.88	*	-13.97		28.29	***
	(2.07)		(-0.38)		(6.03)	
Log CDS spread	-3.75		-3.84		-5.99	***
	(-1.53)		(-1.87)		(-7.73)	
Log fedwire payments	16.98	**	20.96	*	2.01	
	(2.79)		(2.11)		(1.25)	
Change in excess reserve balances	-0.01		0.07		0.02	
	(-0.09)		(0.8)		(1.9)	
Federal funds rate (effective-target)	-37.28	***	0.28		9.74	
	(-3.64)		(0.03)		(1.94)	
Log S&P500 volume	-0.58		5.56		0.81	*
	(-0.22)		(1.24)		(2.55)	
Change in fed liquidity facilities			-0.72	**	-0.2	***
			(-2.68)		(-3.59)	
N. impulse dummies	22		7		56	
N. observations	713		336		923	
Adj. R-squared	0.43		0.42		0.69	
Autocorr. test (p-value):	0.49		0.04	*	0.57	
ARCH test (p-value):	0.15		0.33		0.22	
Normality test (p-value):	0.27		0.37		0.29	

Table 6: **Regressions for core lending to core.** Coefficients are for the solved static long-run equation. Robust t-statistics in parentheses. *** denotes significance at $\alpha = 0.001$, ** at $\alpha = 0.01$, and * at $\alpha = 0.05$. The dependent variable is estimated federal funds loans from core to core expressed in billions of dollars. Estimation begins with a general unrestricted model which includes a constant, 5 lags of the dependent variable, 5 lags of each of the explanatory variables shown in the table, and time dummies for maintenance period day, day before holiday, day after holiday, last day of month, last day of quarter, last day of year, and FOMC announcement day. Model selection is performed using *Autometrics* (Hendry and Doornik (2009)), and only a subset of the retained regressors are shown. Fedwire payments volume excludes identified federal funds transactions. 5-year CDS spread is average of CDS spreads of Citibank, J.P. Morgan, Wells Fargo, Capital One, and U.S. Bancorp. Federal reserve liquidity facilities are the outstanding balance on the Term Auction Facility, Primary Dealer Credit Facility, Commercial Paper Funding Facility, Asset-Backed Commercial Paper Money Market Mutual Fund Liquidity Facility, and the Primary Credit Facility.

	Pre crisis: 8/2/04 - 5/31/07		Early crisis: 6/1/07 - 9/30/08		Late crisis: 1/2/09 - 8/31/12	
Log CDS spread$_i$	0.14		0.06		-0.40	***
	(-0.33)		(-0.29)		(3.36)	
Change in reserve balance$_i$	0.00		-0.02		0.01	
	(-0.14)		(1.36)		(-0.60)	
Month-end dummy	0.02		0.06		-0.01	
	(-0.06)		(-0.51)		(0.07)	
Quarter-end dummy	0.29		-0.79		-0.02	
	(-0.12)		(0.90)		(0.11)	
Change in TAF borrowing$_i$			0.00		0.00	
			(-0.40)		(0.18)	
Constant	0.89		1.46	***	1.35	***
	(-1.13)		(-730.50)		(-37.56)	
N. Observations	5359		1186		1394	
N. Banks	10		10		10	
R-squared	0.005		0.006		0.033	

Table 7: **Panel regressions for core banks' borrowing from GIN.** Robust t-statistics in parentheses. *** denotes significance at $\alpha = 0.001$, ** at $\alpha = 0.01$, and * at $\alpha = 0.05$. The banks in the panel are those that were mostly in the core throughout the entire sample period. The dependent variable is the log of the dollar amount borrowed by bank i from lenders in the GIN component. All specifications include bank-specific fixed effects. TAF=Term Auction Facility.

	Pre crisis: 8/2/04 - 5/31/07		Early crisis: 6/1/07 - 9/30/08		Late crisis: 1/2/09 - 8/31/12	
Log CDS spread$_i$	0.06		-0.14		-0.53	
	(-0.17)		(0.65)		(1.39)	
Change in reserve balance$_i$	0.00		-0.01		-0.03	
	(-0.11)		(0.93)		(0.45)	
Month-end dummy	0.02		0.18		-0.02	
	(-0.23)		(-1.41)		(0.09)	
Quarter-end dummy	-0.14		-1.27		-0.26	
	(0.67)		(1.20)		(0.76)	
Change in TAF borrowing$_i$			0.02		-0.03	*
			(-1.42)		(2.55)	
Constant	0.33		0.06	***	-0.69	***
	(-0.47)		(-9.00)		(5.91)	
N. Observations	5510		1252		1411	
N. Banks	10		10		10	
R-squared	0.001		0.011		0.023	

Table 8: **Panel regressions for core banks' borrowing from other core banks.** Robust t-statistics in parentheses. *** denotes significance at $\alpha = 0.001$, ** at $\alpha = 0.01$, and * at $\alpha = 0.05$. The banks in the panel are those that were mostly in the core throughout the entire sample period. The dependent variable is the log of the dollar amount borrowed by bank i from other banks in the core. All specifications include bank-specific fixed effects. TAF=Term Auction Facility.

	Pre crisis: 8/2/04 - 5/31/07		Early crisis: 6/1/07 - 9/30/08		Late crisis: 1/2/09 - 8/31/12	
Log CDS spread$_i$	-0.02		-0.26	***	-0.15	*
	(0.15)		(5.63)		(2.48)	
Change in reserve balance$_i$	0.02	*	0.00		0.01	
	(-2.50)		(0.67)		(-0.40)	
Month-end dummy	0.10	***	0.02		0.04	
	(-3.78)		(-0.45)		(-1.19)	
Quarter-end dummy	-0.07		-0.24		-0.23	*
	(0.60)		(0.75)		(2.25)	
Change in TAF borrowing$_i$			0.00		0.01	
			(0.38)		(-1.60)	
N. Observations	5510		1252		1411	
N. Banks	10		10		10	
R-squared	n.a.		n.a.		n.a.	

Table 9: **Panel regressions for number of nodes in GIN from which CORE banks borrow from.** Robust t-statistics in parentheses. *** denotes significance at $\alpha = 0.001$, ** at $\alpha = 0.01$, and * at $\alpha = 0.05$. The banks in the panel are those that were mostly in the core throughout the entire sample period. The dependent variable is the number of nodes (institutions) in the GIN component that bank i borrows from. All specifications include bank-specific fixed effects. TAF=Term Auction Facility.

	Pre crisis: 8/2/04 - 5/31/07		Early crisis: 6/1/07 - 9/30/08		Late crisis: 1/2/09 - 8/31/12	
Log CDS spread$_i$	-0.10		-0.16	*	-0.05	
	(1.16)		(2.00)		(0.28)	
Change in reserve balance$_i$	0.01		0.00		0.01	
	(-1.80)		(0.60)		(-0.36)	
Month-end dummy	0.04	*	0.08	**	-0.05	
	(-2.44)		(-3.00)		(0.84)	
Quarter-end dummy	0.01		-0.38		-0.02	
	(-0.19)		(1.22)		(0.20)	
Change in TAF borrowing$_i$			0.00		-0.02	***
			(0.00)		(5.33)	
N. Observations	5510		1252		1411	
N. Banks	10		10		10	
R-squared	n.a.		n.a.		n.a.	

Table 10: **Panel regressions for number of nodes in core from which core banks borrow from.** Robust t-statistics in parentheses. *** denotes significance at $\alpha = 0.001$, ** at $\alpha = 0.01$, and * at $\alpha = 0.05$. The banks in the panel are those that were mostly in the core throughout the entire sample period. The dependent variable is the number of nodes (institutions) in the core that bank i borrows from. All specifications include bank-specific fixed effects. TAF=Term Auction Facility.

Figures
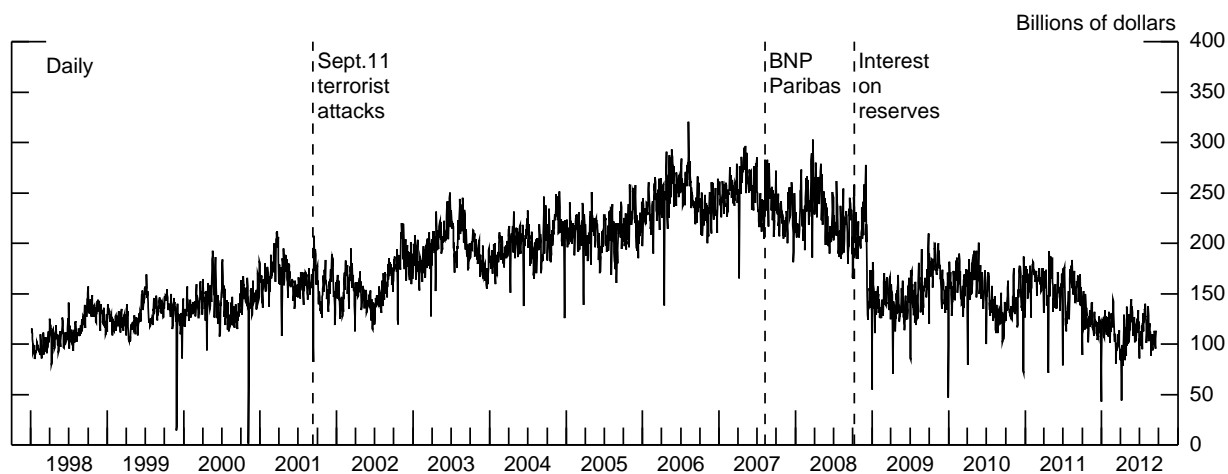
Figure 1: **Federal funds volume, 1998-2012.** "BNP Paribas" line corresponds to August 9, 2007, when it halted redemptions on three of its investment funds citing the evaporation of liquidity in certain segments of the U.S. securitization market. "Interest on reserves" line corresponds to October 6, 2008, when the Federal Reserve announced that it will begin to pay interest on depository institutions' required and excess reserve balances. Source: Authors' calculations using Fedwire data.
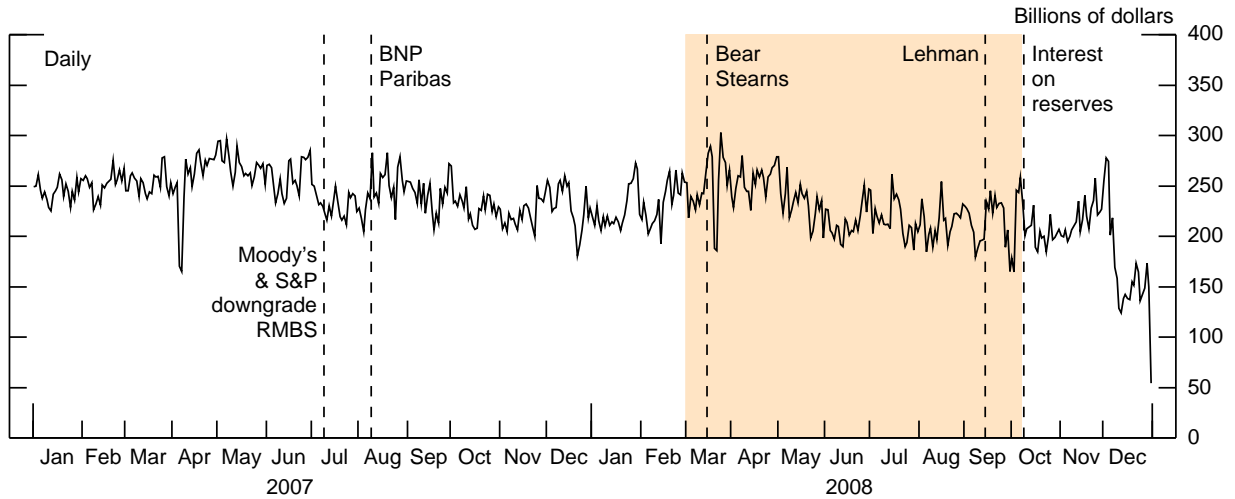
Figure 2: **Federal funds volume, 2007-2008.** Shaded region denotes sample period examined in Afonso, Kovner, and Schoar (2011). "BNP Paribas" line corresponds to August 9, 2007, when it halted redemptions on three of its investment funds citing the evaporation of liquidity in certain segments of the U.S. securitization market. "Bear Stearns" line corresponds to March 17, 2008, when it was acquired by J.P. Morgan. "Interest on reserves" line corresponds to October 6, 2008, when the Federal Reserve announced that it will begin to pay interest on depository institutions' required and excess reserve balances. "Lehman" line corresponds to September 15, 2008, when it filed for bankruptcy. Source: Authors' calculations using Fedwire data.
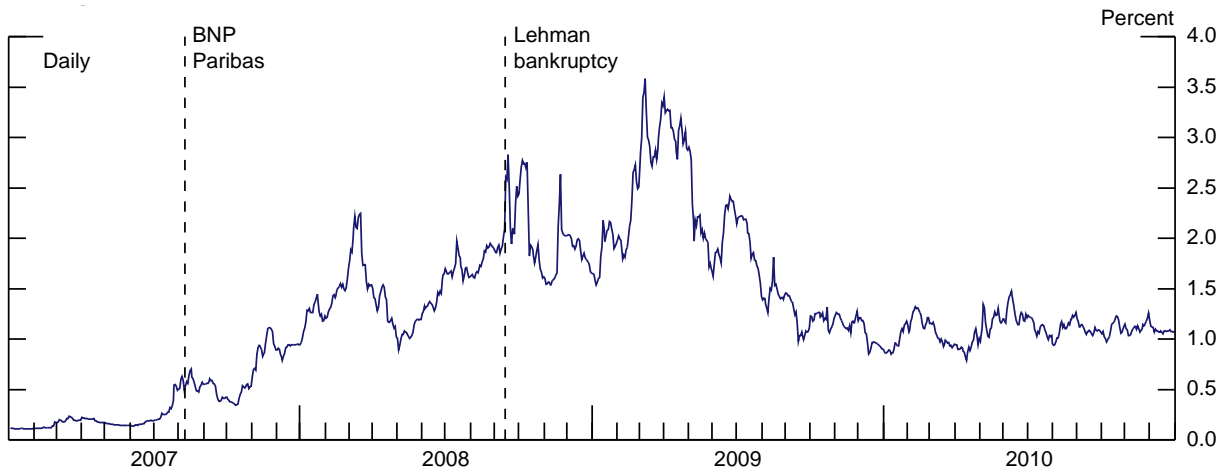
Figure 3: **Average CDS spread of U.S. banks.** Average of 5-year CDS spread of Citibank, J.P. Morgan, Wells Fargo, Capital One, and U.S. Bancorp. "BNP Paribas" line corresponds to August 9, 2007, when it halted redemptions on three of its investment funds citing the evaporation of liquidity in certain segments of the U.S. securitization market. "Lehman" line corresponds to September 15, 2008, when it filed for bankruptcy. Source: Markit Credit Default Swaps (CDS).
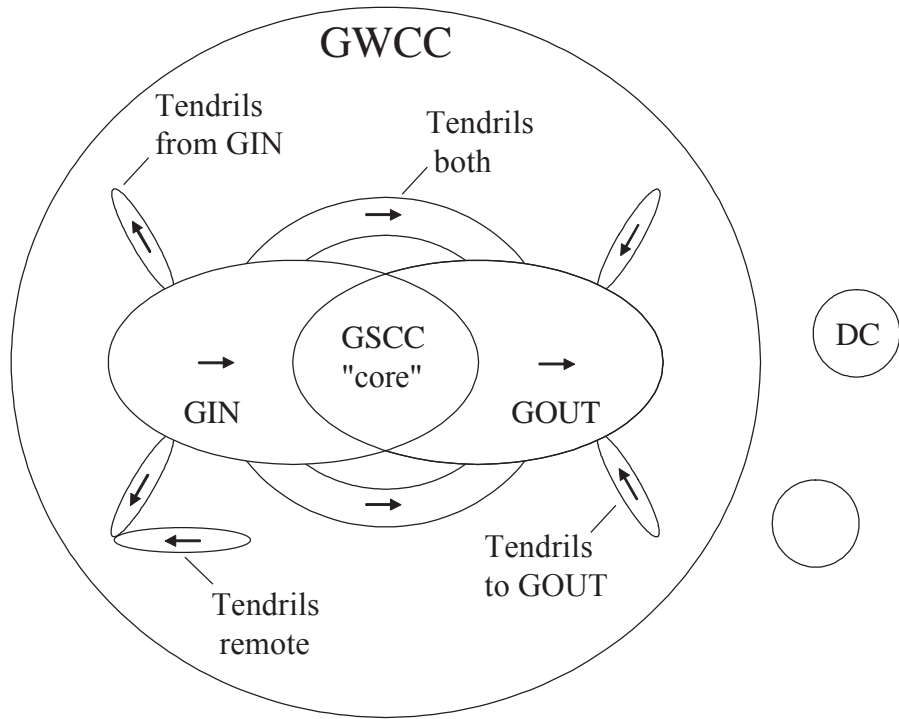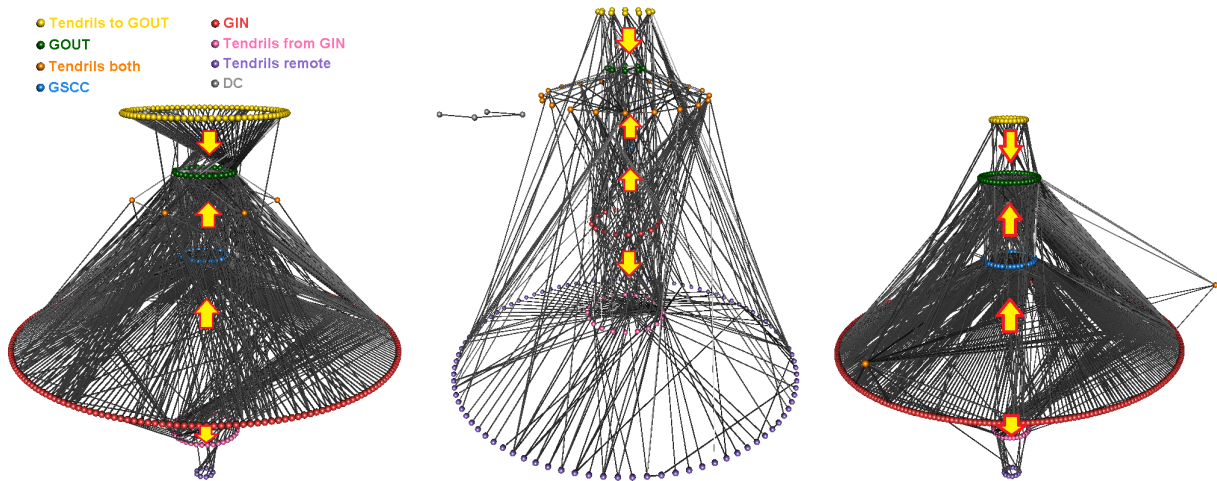
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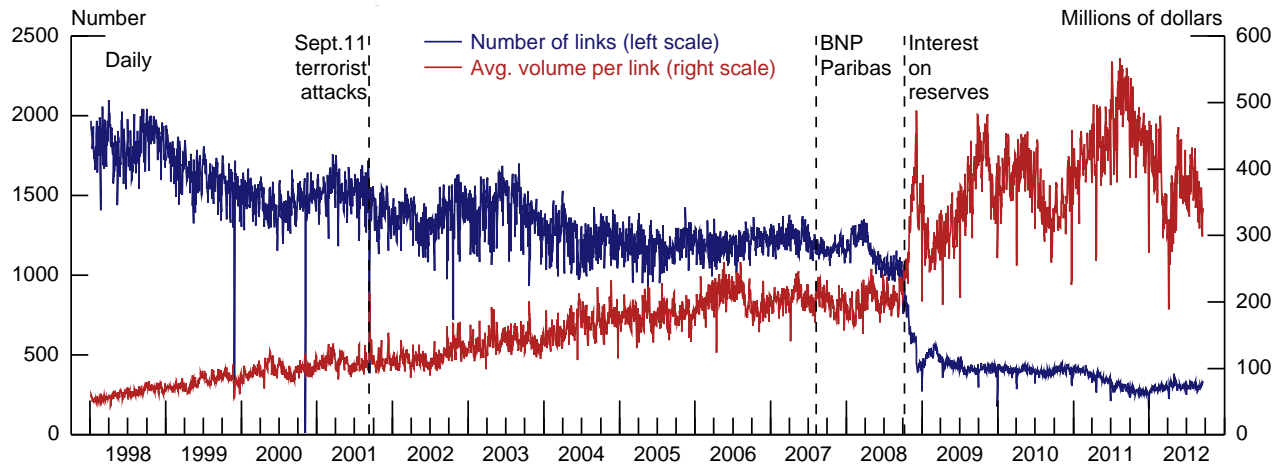
Figure 4: **Number of links and average transaction volume per link, 1998-2012.** "BNP Paribas" line corresponds to August 9, 2007, when it halted redemptions on three of its investment funds citing the evaporation of liquidity in certain segments of the U.S. securitization market. "Interest on reserves" line corresponds to October 6, 2008, when the Federal Reserve announced that it will begin to pay interest on depository institutions' required and excess reserve balances. Source: Authors' calculations using Fedwire data.
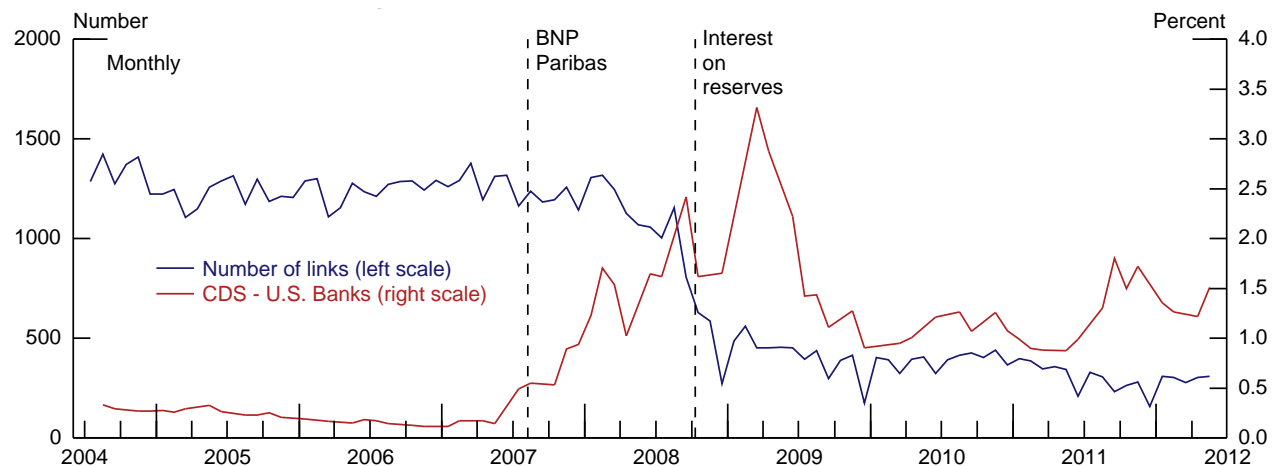
Figure 5: **Number of links and average CDS spread of U.S. banks.** Monthly averages computed using daily data. Red line is the average of the 5-year CDS spread of Citibank, J.P. Morgan, Wells Fargo, Capital One, and U.S. Bancorp. "BNP Paribas" line corresponds to August 9, 2007, when it halted redemptions on three of its investment funds citing the evaporation of liquidity in certain segments of the U.S. securitization market. "Interest on reserves" line corresponds to October 6, 2008, when the Federal Reserve announced that it will begin to pay interest on depository institutions' required and excess reserve balances. Source: For CDS, Markit Credit Default Swaps (CDS); for number of links, authors' calculations using Fedwire data.
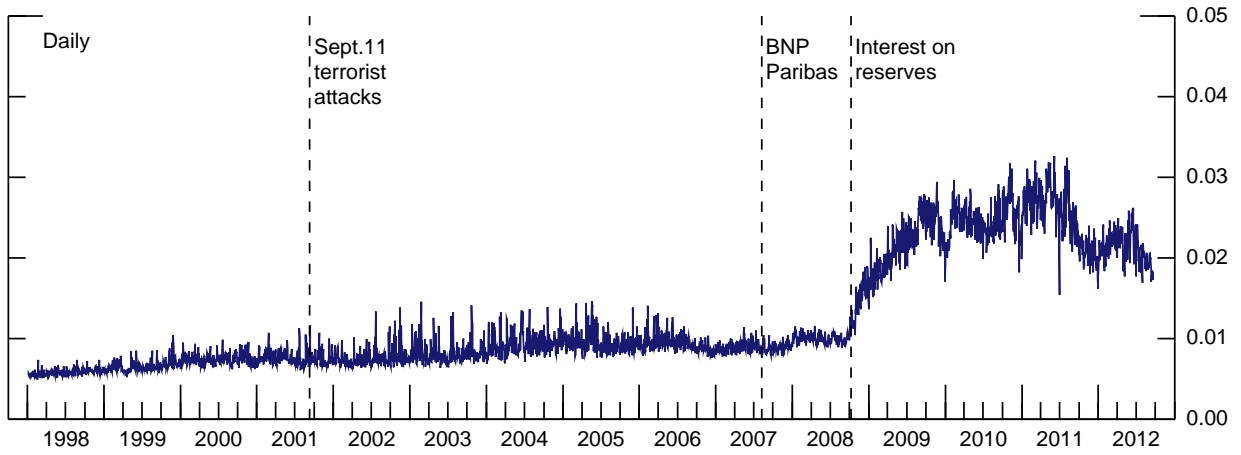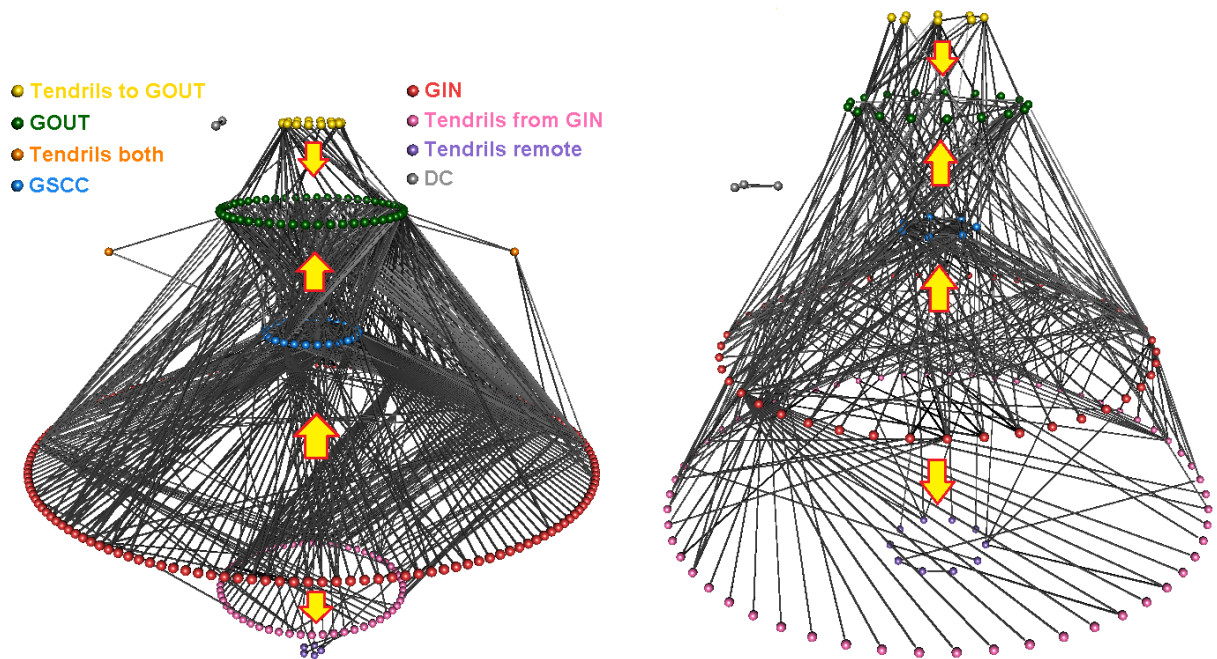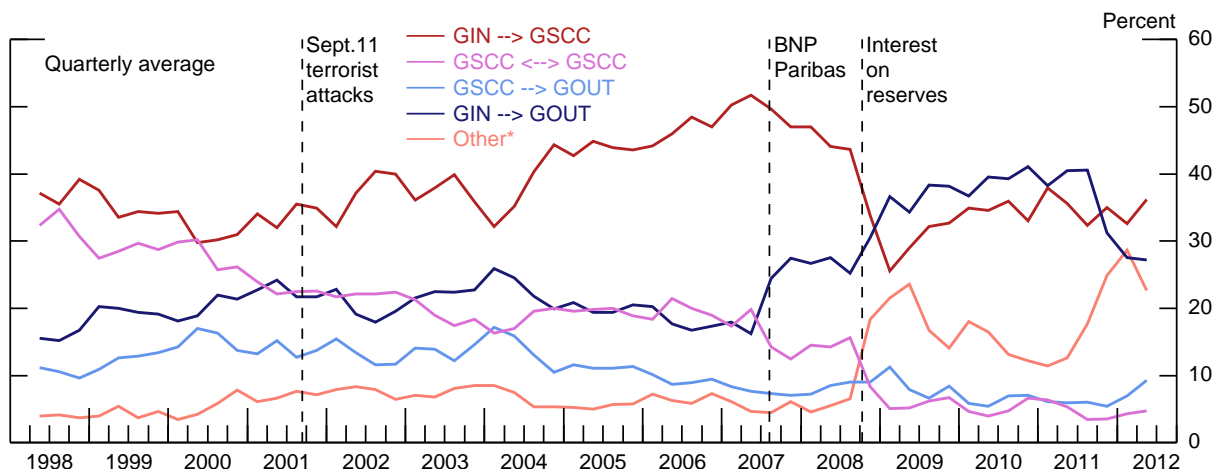
Figure 6: **Degree of completeness, 1998-2012.** "BNP Paribas" line corresponds to August 9, 2007, when it halted redemptions on three of its investment funds citing the evaporation of liquidity in certain segments of the U.S. securitization market. "Interest on reserves" line corresponds to October 6, 2008, when the Federal Reserve announced that it will begin to pay interest on depository institutions' required and excess reserve balances. Source: Authors' calculations using Fedwire data.

Figure 7: **Network components.** Adapted from Soramaki, Bech, Arnold, Glass, and Beyeler (2006).

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Figure 8: **Federal funds network on September 10, 2001 (left panel), September 11, 2001 (middle panel), and September 17, 2001 (right panel).** Arrows denote direction of lending.


Figure 9: **Federal funds network on September 15, 2008 (left panel), and on December 8, 2008 (right panel).** Arrows denote direction of lending.

Figure 10: **Fed funds volume shares by network component, 1998-2012.** * Other comprises transactions involving tendrils and disconnected components. "BNP Paribas" line corresponds to August 9, 2007, when it halted redemptions on three of its investment funds citing the evaporation of liquidity in certain segments of the U.S. securitization market. "Interest on reserves" line corresponds to October 6, 2008, when the Federal Reserve announced that it will begin to pay interest on depository institutions' required and excess reserve balances. Source: Authors' calculations using Fedwire data.
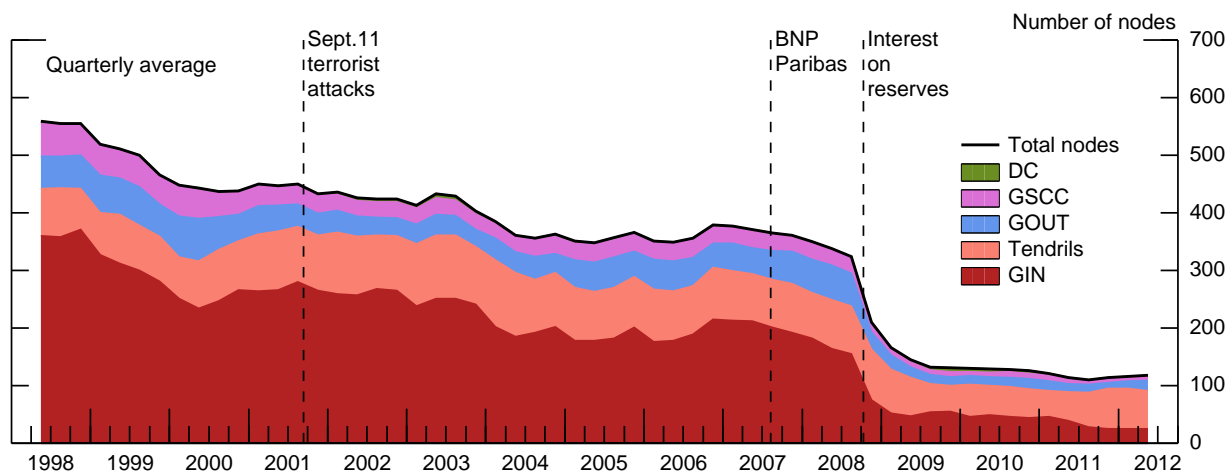

Figure 11: **Fed funds network component size, 1998-2012.** "BNP Paribas" line corresponds to August 9, 2007, when it halted redemptions on three of its investment funds citing the evaporation of liquidity in certain segments of the U.S. securitization market. "Interest on reserves" line corresponds to October 6, 2008, when the Federal Reserve announced that it will begin to pay interest on depository institutions' required and excess reserve balances. With just a few banks in the DC component, the green shaded region is too thin to be visible. Source: Authors' calculations using Fedwire data.
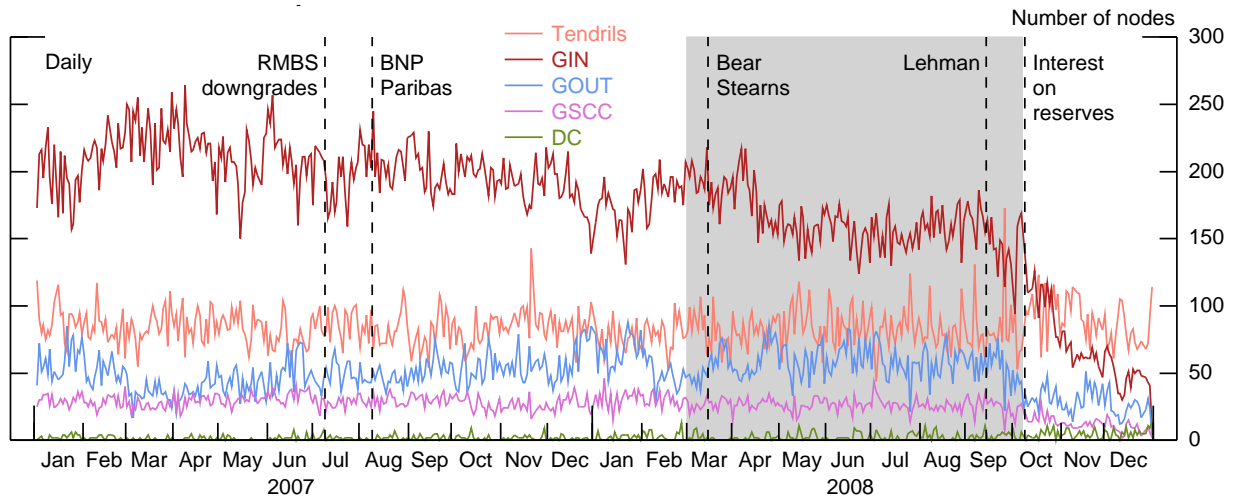
Figure 12: **Fed funds network component size, 2007-2008.** "RMBS downgrades" line corresponds to July 10, 2007, when Moody's and S&P downgraded hundreds of residential mortgage-backed securities. "BNP Paribas" line corresponds to August 9, 2007, when it halted redemptions on three of its investment funds citing the evaporation of liquidity in certain segments of the U.S. securitization market. "Bear Stearns" line corresponds to March 17, 2008, when it was acquired by J.P. Morgan. "Interest on reserves" line corresponds to October 6, 2008, when the Federal Reserve announced that it will begin to pay interest on depository institutions' required and excess reserve balances. "Lehman" line corresponds to September 15, 2008, when it filed for bankruptcy. Shaded region denotes sample period examined in Afonso, Kovner, and Schoar (2011). Source: Authors' calculations using Fedwire data.
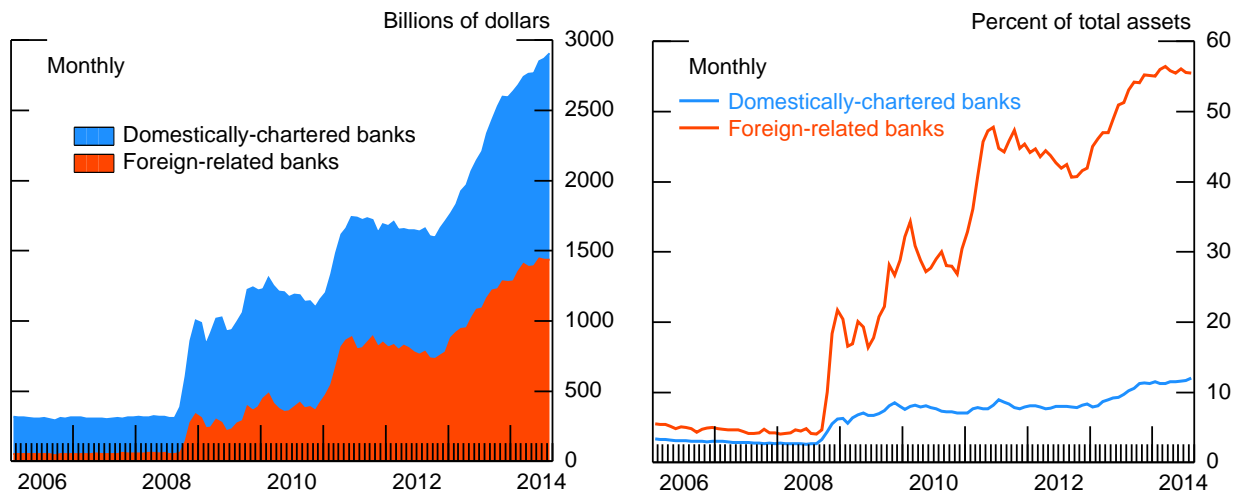
Figure 13: **Balances due from Federal Reserve Banks, and other cash assets of U.S. banks.** Cash assets of domestically-chartered and foreign-related banks operating in the United States, in billions of dollars (left panel), and as a share of total assets (right panel). Cash assets include balances due from Federal Reserve Banks, balances due from depository institutions, as well as vault cash and cash items in process of collection. Source: Federal Reserve H.8 data. These data can be downloaded from: `http://www.federalreserve.gov/datadownload/Choose.aspx?rel=H8`