Essays in Macro-Finance

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by
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<div align="right">Ragnar Enger Juelsrud</div>

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Chapter 1

Introduction and summary

This thesis is motivated by the financial crisis of 2007 and 2008. The financial crises posed a challenge for economics - both in terms of understanding the events that were unfolding and in terms of understanding the effectiveness of the policies that were put in place as a response. Broadly speaking, the first two chapters of this thesis contributes to the existing literature with respect to the former, while the last three chapters contributes with respect to the latter.

During the peak of financial market turmoil, U.S. banks were subject to high rollover risk.[1] Yet, banks kept paying substantial dividends. Such behavior is controversial because high dividend payouts decrease the available liquidity, thereby making banks more susceptible to rollover risk. Commentators have since debated why banks did not decrease dividend payments earlier, whether the dividend payments decreased financial stability and what to do about it. For instance, Scharfstein and Stein (2008) argues that the dividend payouts represented a form of moral hazard and enhanced financial instability. Related to this, Goodhart, Peiris, Tsomocos, and Vardoulakis (2010b) has proposed restricting dividend payouts as a form of macroprudential policy. On the other hand, Acharya, Gujral, Kulkarni, and Shin (2011) argues that banks were afraid that cutting dividends would be seen as a bad signal and as such increase rollover risk. In Chapter 1, Plamen Nenov and I analyze these questions theoretically and empirically. Theoretically, we show that during times of uncertainty and financial market stress, the overall effect of decreasing dividend payments on bank rollover risk is ambiguous. By increasing available liquidity, a reduction in dividends has a direct *resilience effect* – a positive effect on the bank's ability to survive a rollover episode. However, it also has an indirect *signaling effect*, since without perfect information, short-term lenders that decide whether to roll over the bank's debt use the dividend payment to infer the quality of the bank. We show that when the signaling effect is weak and the resilience effect dominates, banks not only become weaker by paying dividends but they also exert a negative externality on other banks. This ends up amplifying financial instability. In contrast, when the signaling effect is strong, banks have incentives to pay dividends in order to manage the rollover crisis. Empirically, we show that consistent with our theory, banks that were more reliant on short-term funding were more reluctant to cut dividend payments. We also show similar patterns across industries - dividend payments are

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[1]Rollover risk is the risk that the bank's short-term lenders would suddenly refuse to roll over their debt.

less volatile in industries which rely more on short-term funding. We then use our framework to analyze the effects of different dividend regulation policies during periods of financial stress. We show that if a policy maker wants to reduce dividend outflows from the banking system, a dividend tax can achieve this while maintaining banks ability to manage a rollover crises.

The model used in Chapter 1 is referred to as a global game. In a global game, many dispersed agents decide whether or not to "attack" a "regime". In the context of a rollover crisis such as the one observed during in 2008, the "regime" can be a bank and "attacking" means that agents refuse to roll over their debt. Such models are often used to study a wide range of crisis phenomena such as bank runs (Goldstein and Pauzner, 2005) or speculative currency attacks (Morris and Shin, 1998). A useful aspect of this class of models is that they allow researchers to study the consequences of deteriorations in the information environment. For instance, does the likelihood of a bank run increase when uncertainty about the health of banks increase? While this has been studied theoretically (Iachan and Nenov, 2015), there is limited empirical evidence. In Chapter 2, Leif Helland, Felipe Iachan, Plamen Nenov and I experimentally test whether increased uncertainty about the quality of the regime makes agents more or less willing to attack the regime. Put differently, we test whether more uncertainty about the quality of a bank makes agents more or less willing to roll over their debt. In theory, more uncertainty would lead agents to be more likely to attack. In a rollover crises application, this would mean that more uncertainty about the bank increases rollover risk. Our main experimental finding is that subjects in the lab do not play as predicted by the theory. Rather, more uncertainty makes subjects more cautious relative to what the theory predicts. In order to explain our findings theoretically, we relax the assumption that agents are rational and instead assume that they have limited depth of reasoning. We then show that this modified model can explain our experimental finding.

The last three chapters evaluate the effectiveness of various post-crisis reforms. The crisis marked the beginning of a new era for economic policy, introducing a wide range of new tools for both stimulating aggregate demand and preventing a new crisis. In terms of stimulating aggregate demand, central banks across the world adopted a wide range of unconventional monetary policy tools such as forward guidance, quantitative easing and negative nominal interest rates. There is limited historical evidence on how effective these tools are in terms of stimulating aggregate demand. At the same time, recent research (Kiley and Roberts, 2017) suggest that they will be a more central part of monetary policy going forward. In Chapter 3, Gauti Eggertssson, Ella Getz Wold and I therefore analyze the effectiveness of negative nominal interest rates in terms of stimulating aggregate demand. Focusing on the pass-through of negative nominal interest rates via the banking sector, we use aggregate and bank level data to document a collapse in pass-through to deposit and lending rates once the policy rate turns negative. A potential explanation for the lack of pass-through to lending rates is the lack of pass-through to deposit rates. Consistent with this, we show that the pass-through of policy rate cuts to lending rates is weaker for banks with higher deposit shares, and that these banks have substantially lower credit growth once the central bank implements negative rates. Overall, these empirical findings suggest that the monetary

policy transmission is substantially weakened with negative nominal interest rates. Motivated by these empirical facts, we construct a macro-model with a banking sector that links together policy rates, deposit rates and lending rates. Once the policy rate turns negative the usual transmission mechanism of monetary policy breaks down. Moreover, because a negative interest rate on central bank reserves reduces bank profits, the total effect on aggregate output can be contractionary.

The second important policy focus was to enhance financial stability. The last two chapters evaluates the effects of increased capital requirements, perhaps one of the most important policy tools put in place after the crisis. Higher capital requirements - the minimum requirement on bank capital ratios - should all else equal make banks less vulnerable to asset losses and hence make them more able to handle the next economic downturn. A large and growing literature, see for instance Gropp, Mosk, Ongena, and Wix (2018), analyzes how banks respond to such regulation and what the consequences are for bank clients. In Chapter 4, Ella Getz Wold and I contribute to this literature by using a 2013 Norwegian policy reform to study how banks react to higher capital requirements and how these adjustments transmit to the real economy. Using bank balance sheet data, we document that banks raise capital ratios mainly by reducing risk-weighted assets. The majority of the reduction in risk-weighted assets is accounted for by a reduction in average risk weights. Consistent with this reduction in average risk weights, we document a substantial decline in credit supply to the corporate sector relative to the household sector. We also show that banks react to higher requirements by increasing interest rates, consistent with the reduction in corporate credit growth being supply driven. We then use administrative loan level tax data on all Norwegian banks and their corporate clients to document a reduction in credit at the loan level and to investigate the consequences of this reduction on the affected firms. The data allows us to focus the effects on all types of firms operating in the economy and this is a key contribution of our paper. We find that a reduction in credit reduces firm-level employment growth - an effect that is driven by the smaller firms.

One of the goals of increasing capital requirements was to reduce systemic risk, i.e. the negative externality that banks impose on the real economy by being under-capitalized during an aggregate downturn. While the measurement of systemic risk has been advanced over the recent years (see for instance Acharya, Pedersen, Philippon, and Richardson 2017) there is limited evidence on how effective capital requirements are in terms of decreasing systemic risk. In the final chapter of the thesis, I analyze this question. Specifically, I use a quasi-natural experiment - the EBA capital exercise in 2011 - to identify the causal effect of increased capital requirements on banks systemic risk. My main finding is that systemic risk *increases* in response to increased capital requirements. I find that the effect is larger for banks that initially have high systemic risk. I show that the negative effect of capital requirements on systemic risk is driven primarily by the adverse effect of capital requirements on the market value of bank equity. Finally, I discuss the implications of my findings for the design of policies aimed at recapitalizing the financial system. A take-away from the paper is that policy makers who want to reduce systemic risk should consider forcing banks to increase capital rather than increase capital ratios.

The last three chapters suggest that there is little reason for complacency among policy makers. In fact, the research in this thesis indicates that some of the policies implemented may have been less effective than believed. Clearly, there is scope for more research, both in terms of evaluating the effectiveness of financial regulatory reform and in terms of understanding how to stimulate the economy when the next recession hits.

Chapter 2

Dividend Payouts and Rollover Crises

with Plamen T. Nenov

2.1 Introduction

The dividend policies of banks received much attention in the wake of the 2007-2008 financial crisis. The U.S. banking sector maintained large dividend payouts throughout 2007 and 2008, even as losses were increasing rapidly (Acharya, Shin, and Gujral, 2009). Aggregate dividends paid by U.S. banks in 2008 exceeded their aggregate earnings by about 30 percent (Floyd, Li, and Skinner, 2015). Moreover, for the 19 largest U.S. banks, the dividends paid from the fall of 2007 to the fall of 2008 correspond to roughly 50 percent of the funds that were used in bailing out these banks (Rosengren et al., 2010).

One explanation for banks dividend policies during the early stages of the financial crisis is that they reflected a form of moral hazard. Scharfstein and Stein (2008) argue that banks engaged in "risk shifting" and that their dividend policies were "... an attempt by shareholders to beat creditors out the door". Another explanation focuses on a potential signaling role of dividends. Acharya, Gujral, Kulkarni, and Shin (2011) suggest that U.S. banks were worried that cutting dividends could induce a run by their short-term creditors. Floyd, Li, and Skinner (2015), and Hirtle (2014) compare the evolution of dividend payouts and share repurchases by U.S. banks – two ways to return cash to shareholders – prior to and during the crisis. While dividends and share repurchases followed similar patterns prior to the crisis, banks cut their share repurchase programs substantially in 2007-2008 but maintained dividend payments.[1]

Can these two views of dividend payments both play a role to explain bank behavior? Also,

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[1] Such a "signaling" view goes beyond dividend payouts and concerns a number of bank actions that seem to worsen bank's proximate liquidity position in times of financial stress. For example, Duffie (2010) provides a description of a hypothetical dealer bank's actions in response to financial stress. He notes that the bank "... takes actions that worsen its liquidity position in a rational gamble to signal its strength and protect its franchise value. [The bank] wishes to reduce the flight of its clients, creditors, and counterparties." Such actions include compensating clients for losses on investments arranged by the bank or continuing with OTC derivative trades that reduce available liquidity. Although these actions are not our proximate motivation, our theoretical framework can be interpreted more broadly and used to analyze their signaling effects as well.

is there an informational role of dividends when banks face dispersed short-term lenders that try to coordinate their decisions to roll over maturing debt? Finally, what is the impact of dividend regulation policies on rollover risk when both "risk shifting" and "signaling" motives are present? In this paper, we address these questions by examining theoretically the role of dividends when banks are subject to coordination-based rollover crises or runs (Diamond and Dybvig, 1983).

In our framework, a bank (owner) can use dividend payouts to precipitate its failure and "beat creditors out the door" during a rollover episode. We call this direct effect on survival the *resilience effect* of dividends. Absent any other interactions, lowering dividends increases resilience and improves financial stability. However, dividends also convey information about the bank's underlying assets and its ability to survive a rollover episode. Thus, a bank's dividend policy affects the incentives of short-term lenders to roll over their debt. We call this second indirect effect on survival the *signaling effect*. Whenever the signaling effect is sufficiently strong, some banks use their dividend policies to help lenders coordinate their rollover decisions. Therefore, even though a bank appears to be reducing its resilience by paying dividends, it may in fact be reducing the impact of the rollover episode.

We now provide further details for our analysis. We consider a bank that is financed by a continuum of short-term lenders (or lenders, for short).[2] Lenders simultaneously choose whether to roll over their maturing debt but face a coordination problem – if a sufficient number of lenders refuse to roll over (run, for short), then the bank does not have enough liquidity to repay all lenders and is forced to fail. In that case, an individual lender is better off running than rolling over. Lenders, however, have incomplete and dispersed information about the quality of the bank's portfolio, which also determines the total liquidity available to the bank.

At an initial stage, prior to the rollover episode, the bank (owner) chooses a dividend to maximize its payoff. It derives a positive payoff from consuming the dividend paid out but incurs a cost in terms of a reduction in the value of bank assets, *conditional* on surviving the rollover episode. Therefore, a bank which expects to fail the rollover episode (and does not care about its continuation value) has an incentive to pay as much in dividends as it feasibly can. Additionally, we assume that while liquidating assets is costly for any bank, conditional on survival, it is relatively more costly for banks with lower portfolio quality. Therefore, in the absence of a rollover episode, higher quality banks choose to pay higher dividends. In that case higher dividends constitute good news about a banks's portfolio quality.

For simplicity, we start our analysis by restricting the choice of dividends to one of two levels – either pay a fixed positive dividend or do not pay any dividend. In that setting we compare two cases. First, we switch off the signaling effect completely by assuming that lenders do not observe the dividend policy of the bank and instead observe an exogenous private signal about the bank's type. In that case only the resilience effect is present, and a bank that pays out a dividend ends up increasing the liquidity outflow it will eventually experience. Since a higher liquidity outflow can be

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[2]Even though we motivate and frame our analysis in the context of banking and dividend payouts, the implications are applicable more generally to any firm that is subject to rollover risk and which can take an action that has a direct negative effect on its liquidity position but also conveys information to lenders.

met only by a bank of higher quality, the option to make a dividend payment increases the fraction of failing banks.

Moreover, in this case banks impose a negative externality on other banks when they choose to pay a dividend (and end up failing) due to the rollover decision of lenders. Specifically, strengthening the incentives to pay a dividend induces more banks to choose to pay a dividend and fail, increasing the fraction of failing banks. This in turn makes lenders less willing to roll over their debt for *all* banks, which induces more banks to choose to fail. The resulting equilibrium feedback, thus, ends up amplifying financial instability.

Next, we introduce the signaling effect by assuming that the lenders observe the bank's dividend and make inferences about the bank's type based on that information and their prior beliefs. In that case, the dividend choice of the bank acts as an endogenous signal about the bank's type. To ensure equilibrium uniqueness, we additionally assume that lenders observe the dividend with small idiosyncratic noise. Therefore, while we think of dividends as publicly-available information, we do not model it as public information in the game-theoretic sense.[3]

When lender signals are sufficiently precise, the signaling effect is strong, so paying a dividend can actually *decrease* the total liquidity outflow that the bank experiences. There are two reasons for this stark outcome. First, observing higher dividends constitutes good news about the bank's survival if there is a sufficiently large share of high-quality banks, which always survive the rollover episode and pay a dividend, and of low-quality banks, which never survive the rollover episode and cannot pay a dividend. In that case, paying a dividend allows a bank to pool with high-quality surviving banks and separate from very low-quality failing banks. Second, the high signal precision of lenders implies that the dividend choice of the bank influences the actions of a large group of these lenders. Thus, while the direct effect of paying a dividend is to reduce resilience and increase the liquidity outflow from the bank, the indirect effect through the rollover actions of lenders decreases the liquidity outflow from the bank. When lender signals are sufficiently precise and lenders are sufficiently coordinated, the indirect effect dominates the direct effect.

We then consider a richer model, in which the bank can pay any non-negative dividend that is feasible given its portfolio quality. In that case, a strong signaling effect lowers the sensitivity of dividends to the bank fundamentals relative to their dividend payout in the absence of rollover. Put differently, surviving banks with very different fundamentals may choose to pay similar dividends in equilibrium. Intuitively, banks with lower fundamentals have strong incentives to distort their dividends upward and pay a dividend similar to higher-quality banks to help lenders coordinate on rolling over. On the other hand, since lenders only care about whether the bank fails or survives the rollover episode (rather than the specific bank type), the dividend payments of banks with higher

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[3]We are not the first to treat publicly-available information in this way (see, e.g. Woodford (2003a), Myatt and Wallace (2014), Kolbin (2015), Angeletos and Lian (2016a), or Gaballo (2016)). If dividends are common knowledge, the economy trivially admits multiple equilibria. Introducing a small amount of private noise in the observation of dividends removes the common knowledge aspect from the dividend signal. Note, also, that adding a small amount of private noise to a signaling action in a global coordination game does not necessarily lead to a unique equilibrium (e.g. Angeletos, Hellwig, and Pavan, 2006). Nevertheless, under certain conditions, there will be a unique equilibrium in our framework.

fundamentals are already interpreted by (most) lenders as evidence that the bank will survive the rollover episode, so any upward distortion in dividends for those bank types has only a small effect on the lenders' behavior.[4]

We also discuss some policy implications of our framework. We show that restricting dividend payouts during a rollover crisis has an *ambiguous* effect on bank failure. Intuitively, restricting dividends fully removes the bank's risk-shifting incentives. However, it also shuts down the signaling effect, impacting the bank's ability to manage the rollover episode. If the rollover crisis is sufficiently severe and the risk-shifting incentives are weak, restricting dividends ends up increasing the bank failure threshold (and vice versa). In contrast, we show that a (proportional) tax on dividends *unambiguously* reduces the bank failure threshold irrespective of the strength of the risk-shifting incentives or the severity of the rollover crisis. The reason is that a dividend tax both weakens the risk-shifting incentives but also maintains the signaling effects of dividends.

Finally, we discuss the empirical relevance of our theory. One implication is that rollover risk combined with a strong signaling effect reduce the sensitivity of dividends to fundamentals. Consistent with this, we show that banks which were more reliant on short-term funding prior to the crisis were less likely to cut dividends during the crisis. We also find cross-industry support for this link by showing that dividend payments are more stable in industries in which firms have greater reliance on short-term funding.

Literature review   Our paper is related to several strands of research. First, it is related to the growing literature on bank dividend payouts, particularly during a financial crisis, and the optimal policy response to those (Acharya, Le, and Shin (2017), Floyd, Li, and Skinner (2015), Hirtle (2014), Cziraki, Laux, and Loranth (2016)). Acharya, Le, and Shin (2017) study a model of bank dividend payouts, in which risk shifting by the bank equity holders because of a possible low future franchise value is an important motive for paying dividends. When banks are linked through an inter-bank market, there is an additional dividend externality that may lead to a systemic crisis, since a higher dividend payout by one bank makes it less likely to repay its inter-bank claims. This, in turn, reduces the franchise value of the bank's creditors and strengthens their incentives to risk shift. Our modeling approach complements this framework by studying the informational role of dividends when banks are exposed to a coordination-based run. When the signaling effect of dividends is weak or absent we also uncover a negative dividend externality that banks impose on other banks, which reduces overall financial stability. However, rather than arising from direct spillovers via bank linkages, in our model, spillovers between banks arise through the inference of lenders and their rollover decisions.

The informational role of dividends in our model relates our paper to the seminal work of Bhattacharya (1979) and a large subsequent literature (Miller and Rock (1985), John and Williams (1985), Hausch and Seward (1993), Guttman, Kadan, and Kandel (2010), Baker, Mendel, and

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[4]In the limit, as lenders get arbitrarily precise signals and are almost perfectly coordinated, the incentives to compress dividend payouts are so strong for surviving banks around the failure threshold so that, locally, banks pool on their dividend payouts.

Wurgler (2016)). Bhattacharya (1979) argues that in the presence of asymmetric information about the prospects of a firm, dividends can serve as a signal to outside investors. In his paper, stronger firms have incentives to separate from weaker firms to ensure favorable stock valuations. In contrast, in our environment with coordination-based crises, surviving banks of intermediate strength have incentives to pay dividends similar to those of stronger banks and separate from very weak banks. Thus, our results are related to the partial pooling result of Guttman, Kadan, and Kandel (2010). However, while in their framework a partial pooling equilibrium is one of many possible equilibria (including a fully separating equilibrium), in our framework, the partial pooling equilibrium is unique (given some conditions). Furthermore, the pooling is only local (around the bank failure cutoff) in the limiting case where lenders have arbitrarily precise signals. Away from that limit and when dividend choices are unrestricted, surviving banks choose different (albeit similar) dividends.

Our paper is related to the large literature on global games of regime change (e.g Carlsson and Van Damme (1993) and Morris and Shin (1998)) and particularly to global game models of bank runs (Goldstein and Pauzner (2005), Rochet and Vives (2004)) and rollover crises (Morris and Shin (2004)).[5] We contribute to this important literature by analyzing how banks use their dividend payouts to manage the rollover crisis. In addition, while most of these models assume an exogenous information structure for lenders or an exogenous resilience level for banks, both the information structure of lenders and the resilience level of banks are endogenous in our model.

Our paper is particularly related to models of signaling in global games. Angeletos, Hellwig, and Pavan (2006) and Angeletos and Pavan (2013) consider a regime-change game in which the regime can undertake a costly policy action to influence the cost for agents of attacking. They show that the information conveyed by the policy action may restore multiplicity. Edmond (2013) studies a model of regime-change in which the regime can engage in costly manipulation of the private information of agents considering staging a revolution. In equilibrium, agents try to infer the true type of the regime given the signals they observe. In his framework there is a unique equilibrium.

As in Edmond (2013), our economy may also admit a unique equilibrium despite the signaling effect of the bank's actions and the endogenous information structure that arises. Relative to Edmond (2013), we are motivated by a different question and consider a different environment. In particular, we study how a bank optimally chooses its dividend policy when faced with a coordination-based run, while he studies how a regime engages in costly manipulation of agents' private signals about its type (i.e. propaganda). In our framework, paying out a dividend has a direct positive payoff to the bank, while in Edmond (2013) the regime incurs a cost when manipulating the agents' information. Thus, in our model a bank that is certain it would fail the rollover episode pays out dividends, while in his framework, a regime that is certain that regime change will take place does not try to manipulate the agents' beliefs. Also, in our framework, the direct effect of paying out dividends is to weaken the ability of the bank to survive the rollover episode, so it is not clear *a priori* if paying out dividends increases or decreases the bank failure threshold. In Edmond (2013), the costly action of manipulating agents' information does not influence directly the ability of the

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[5]More recently, Vives (2014) uses a global games model of bank runs to analyze liquidity regulation.

regime to survive, so the regime's action cannot be destabilizing.

Goldstein and Huang (2016a) study how a regime can increase the probability of survival by committing to abandoning the status quo for some fundamentals. However, the information transmission that takes place in their model, and which ends up stabilizing the regime, is more in the spirit of the Bayesian persuasion literature (Kamenica and Gentzkow, 2011) rather than through sending a costly signal.[6]

Finally, in its treatment of how the endogenous information structure induced by bank's dividend policies affects financial stability, our paper is related to the literature on information disclosure and financial stability (for instance from stress-testing as in Bouvard, Chaigneau, and Motta (2015), Faria-e Castro, Martinez, and Philippon (2016), and Goldstein and Leitner (2016), or credit ratings as in Goldstein and Huang (2016b), and Holden, Natvik, and Vigier (Forthcoming)) and also to papers studying the effects of information quality and transparency on stability (Iachan and Nenov (2015), Moreno and Takalo (2016)). In contrast to many of these papers, we focus on information generated by one of the parties in the rollover game, which maximizes its own payoff, rather than a third party (i.e. a regulator) who has an explicit objective to improve financial stability. Thus, the private incentives to pay dividends in our model are not necessarily aligned with concerns for financial stability.

2.2   Model

Consider an economy with three periods, $t \in \{0, 1, 2\}$. There is a bank with an exogenously given asset and liability structure at the beginning of $t = 0$. The bank has a continuum of short-term creditors who make rollover decisions on their debt at $t = 1$.

2.2.1   The bank

We let $\theta \in \mathbb{R}$ parametrize the portfolio quality of the bank (its "fundamentals"). A higher θ means stronger fundamentals. At the beginning of $t = 0$, the bank holds a portfolio consisting of assets with different $t = 0$ liquidation values and $t = 2$ payoffs. At $t = 0$, the bank can make changes to its asset structure. Specifically, it can convert part of its asset portfolio into liquid assets (cash and cash-like instruments) of size l. l is obtained by selling part of the portfolio or borrowing against it as collateral. Out of l the bank chooses a dividend payment d to make at $t = 0$. The bank uses the residual, $g = l - d$, to meet redemptions by short-term lenders at $t = 1$ (see below). Therefore, g captures the (endogenous) resilience of the bank.

We denote the $t = 2$ value of the remaining part of the bank's asset portfolio *conditional on surviving the rollover episode at $t = 1$* by $v(\theta, l)$. $v(\theta, l)$ is twice continuously differentiable, with $v_\theta > 0$, $v_l < 0$, and $v_{ll} < 0$. Therefore, we assume that the value of the remaining part of the bank's portfolio is strictly increasing in θ. It is decreasing in l, since holding cash and cash-like instruments

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[6]Shapiro and Skeie (2015) also study a model of signaling and banking crises. However, in their paper the sender of the costly signal is a policy maker rather than the bank itself. Also, runs on banks are not due to a coordination failure as in our framework.

is assumed to yield a lower return than the long-term loans that the bank is initially endowed with. We assume it is concave in l, since the bank has to sell progressively more illiquid assets to get an additional dollar in cash. In addition, we assume that $v_{l\theta} > 0$. Therefore, while liquidating assets is costly for any bank, conditional on survival, it is relatively more costly for banks with lower θ. This is a single-crossing condition, and as we show below (Proposition 2.1), it implies that in the absence of a rollover episode banks with higher θ would choose to pay higher dividends. While we will work with this general form throughout the paper, below we present some possible (partial) microfoundations for this asset structure.

Given the properties of $v(\theta, l)$, there is a limit on the maximum available liquid assets that a bank can obtain at $t = 0$ denoted by $\bar{\ell}(\theta)$, which satisfies

$$v\left(\theta, \bar{\ell}(\theta)\right) = 0. \tag{2.1}$$

By the properties of v, $\bar{\ell}(\theta)$ is strictly increasing in θ (i.e. $\bar{\ell}' = -v_\theta/v_l > 0$).

The $t = 0$ liabilities of the bank consist of dispersed short-term debt that matures at $t = 1$ with total face value normalized to 1. The short-term debt is held by a unit-measure continuum of lenders, who at $t = 1$ choose whether to redeem it or roll it over into $t = 2$. The bank may fail at $t = 1$, if it does not have enough liquid assets to meet redemptions by short-term lenders. Specifically, if A denotes the fraction of short-term lenders that refuse to roll over, then the bank survives iff

$$g \geq A. \tag{2.2}$$

The expected $t = 2$ payoff of the bank owner conditional on surviving the rollover episode is given by $W_2(v, A)$. That payoff may, in general, depend on the value of remaining assets and on the fraction of short-term lenders that have refused to roll over their debt. However, to simplify the analysis, we will be working with $W_2(v, A) = v$. Hence, conditional on surviving the rollover episode at $t = 1$, there is no conflict of interest between the remaining short-term lenders and the bank owner, so that the bank owner cares about the full residual value of the bank's assets.[7] Therefore, we can write the bank owner's $t = 0$ payoff as

$$W(\theta, g, d, A) = \lambda d + \mathbf{1}_{\{g \geq A\}} v(\theta, d + g), \tag{2.3}$$

where $\mathbf{1}_{\{g \geq A\}}$ is an indicator for whether the bank survives the rollover episode at $t = 1$ and $\lambda > 0$ parametrizes the degree to which the bank owner cares about paying out a dividend at $t = 0$ versus waiting for assets to mature.

Since the bank owner is assumed to care about the full residual value of assets at $t = 2$, while

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[7]Assuming that the bank owner cares only about his expected $t = 2$ equity payoff net of promised payments to maturing short-term lenders would strengthen the bank owner's incentives to pay out dividends and induce the bank's failure even when the bank has the resources to survive a rollover episode. Since such incentives are already present when the bank owner is assumed to care about the full residual value of the bank's assets, allowing for a more general continuation payoff for the bank owner will not change the qualitative predictions of our model but will come at a substantial reduction in tractability.

the dividend payoff carries a direct private benefit to him, one can interpret a lower value of λ as a proxy for the strength of corporate governance and the alignment of interests between equity and debt holders within the bank. Conversely, the higher is λ the stronger the incentives of the bank owners to "beat creditors out the door".

2.2.1.1   Microfoundations

We now provide some (partially) microfounded examples for $v(\theta, l)$. Consider the asset portfolio of the bank and suppose that assets are indexed according to their liquidation (or collateral) value. We denote this index by $a \in [0,1]$ and assume, without loss of generality, that asset liquidity is decreasing in a. Therefore, cash and cash-like assets have a liquidity index of $a = 0$, while fully illiquid assets have an index of $a = 1$. In between are partially illiquid assets which the bank can sell or borrow against but at a discount. Specifically, let $\rho(a, \theta) \in [0,1]$ denote the $t = 0$ liquidation discount or the haircut which is applied to assets with index a if the bank borrows against them. Therefore, for cash and cash-like assets $\rho(0, \theta) = 0$ and for fully illiquid assets $\rho(1, \theta) = 1$. Also, let $X(a, \theta)$ denote the expected $t = 2$ payoffs of assets with liquidity index a if left until maturity. Therefore, the $t = 0$ liquidation value of assets with liquidity index a is $(1 - \rho(a, \theta)) X(a, \theta)$.

Given this indexing, a bank that seeks to obtain l units of cash at $t = 0$ first liquidates/borrows against assets with liquidity index $a = 0$ and then moves on to assets with a higher liquidity index. Specifically, let $\tilde{a}(l, \theta)$ denote the index of the marginal assets that a type θ bank has to liquidate or borrow against to satisfy its demand for cash. Then $\tilde{a}$ is implicitly defined by

$$l = \int_0^{\tilde{a}(l,\theta)} (1 - \rho(a, \theta)) X(a, \theta) \, da. \tag{2.4}$$

The remaining part of the bank's asset portfolio has an expected $t = 2$ value of

$$v(\theta, l) \equiv \int_{\tilde{a}(l,\theta)}^1 X(a, \theta) da. \tag{2.5}$$

Below we provide two specific structures for X and ρ, which result in an residual asset function, $v(\theta, l)$, with the properties assumed in Section 2.2.1.

Example 1: Higher $\theta \Rightarrow$ higher asset payoffs.

Suppose that ρ and X are continuously differentiable, and that $X_\theta > 0$. This can arise because a high θ bank has better quality assets with higher expected payoffs or a better monitoring technology than a low θ bank. Alternatively, it can be the case that a high θ bank has more assets (for the same amount of liabilities) compared to a low θ bank. Also, let $\rho(a, \theta) = \rho(a)$. By definition, $\rho_a > 0$. In Appendix A.1 we show that these assumptions imply that $v_\theta > 0$, $v_l < 0$, $v_{ll} < 0$, and $v_{\theta l} > 0$.

Example 2: Higher $\theta \Rightarrow$ more liquid assets.

Suppose that ρ and X are continuously differentiable and let $X(a, \theta) = X(a)$. Also, suppose that $\rho_\theta < 0$. This can arise because a high θ bank has higher-quality assets, which are easier to liquidate or borrow against compared to a low θ bank. Alternatively, a high θ bank may have a superior asset liquidation technology, for example, because it is a market maker in some dectentralized asset markets and can meet potential buyers with a higher probability. Finally, it may be the case that a high θ bank has better reputation than a low θ bank due to a history of repayment of liabilities, so it can borrow against the same asset with a lower haircut compared to a lower θ bank. In Appendix A.1 we show that these assumptions imply that $v_\theta > 0$, $v_l < 0$, $v_{ll} < 0$, and $v_{\theta l} > 0$.[8]

2.2.2   The lenders

The lender side of the rollover game is standard (e.g. Morris and Shin, 2004). There is a unit-measure continuum of short-term creditors of the bank, which we refer to as the lenders. The lenders can either roll over their debt or refuse to roll over (run, for short). Lenders take their decisions at $t = 1$. If a lender runs at $t = 1$, she obtains

$$\pi_1(A, g) = 1,$$

which is the (normalized) face value of her short-term debt. If she rolls over at $t = 1$, she obtains

$$\pi_0(A, g) = \begin{cases} B & : g \geq A \\ k_0 & : g \leq A \end{cases}.$$

We assume that $k_0 < 1$, i.e. the payoff from rolling over is lower than the payoff from running if the bank fails. Conversely, we assume that $B > 1$, i.e. the payoff from rolling over is higher if the bank survives. Therefore, lenders' actions are strategic complements. We denote the net payoff from running versus rolling over by

$$\pi = \pi_1 - \pi_0,$$

so

$$\pi(A, g) = \begin{cases} 1 - B < 0 & , g \geq A \\ 1 - k_0 > 0 & , g < A \end{cases}.$$

With perfect information about the bank's type and the actions of the other agents, a lender runs iff $\pi \geq 0$.[9]

We assume that the lenders have some prior beliefs over θ distributed according to a distribution function F_p, which admits a density.[10] Lenders observe additional information, which we detail in

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[8]Clearly, the conditions given in the two examples are only sufficient for obtaining a residual asset function with the desired properties, and one can obtain such an asset function in more general environments.

[9]We assume that a lender that is indifferent between running and rolling-over ends up running.

[10]In Section 2.3 we will need to impose some conditions on the prior, since with two dividend levels, the priors remain important for the lenders' inference. In Section 2.4, we will assume that lenders have a uniform prior about θ

Section 2.3 below. Since the information will be heterogeneous across agents, we will denote the expectation (resp. probability) with respect to lender i's information set by E_i (resp. $\Pr_i \{.\}$). Therefore, the expected net payoff from running versus rolling over is

$$E_i \left[\pi \left(A, g \right) \right] = \left(1 - B \right) \Pr_i \{ g \geq A \} + \left(1 - k_0 \right) \left(1 - \Pr_i \{ g \geq A \} \right). \tag{2.6}$$

Dividing by $(B - 1) + (1 - k_0)$ and defining

$$p \equiv \frac{1 - k_0}{(1 - k_0) + (B - 1)} \in (0, 1),$$

a lender i runs iff

$$\Pr_i \{ g \geq A \} \leq p. \tag{2.7}$$

Thus, as is standard in regime-change games, p parametrizes how aggressive lenders are when taking their actions. As p increases, the incentives of the lenders to run are strengthened. Finally, we define a normalized expected net payoff from running by

$$\hat{\pi}_i = p - \Pr_i \{ g \geq A \}, \tag{2.8}$$

so that a lender i runs iff $\hat{\pi}_i \geq 0$. In our analysis below, we will work with this object when characterizing the lenders' actions.

2.2.3 Dominance regions

We assume that there exist lower and upper dominance regions.

- *Lower dominance region:* There exists a $\underline{\theta}$, such that for $\theta < \underline{\theta}$, $\bar{\ell} (\theta) < 0$.

- *Upper dominance region:* There exists a $\overline{\theta}$, such that for $\theta > \overline{\theta}$, $\bar{\ell} (\theta) > 1$, and $\lambda \bar{\ell}(\theta) < v(\theta, 1)$.

- *Multiplicity region:* For $\theta \in \left(\underline{\theta}, \overline{\theta} \right)$, $\bar{\ell} (\theta) \in (0, 1)$.

Therefore, banks with very weak fundamentals are insolvent and fail with probability one for any $A \in [0, 1]$. Conversely, banks with very strong fundamentals can meet all demands for withdrawals. Furthermore, it is never optimal for such banks to liquidate all their assets at $t = 0$.[11] In between, whether a bank can survive or not, depends on whether lenders coordinate on running or rolling over. If all lenders run, then the bank cannot survive, and if all lenders roll over, the bank can survive. The equilibrium concepts that we work with are standard and are included in Appendix A.1.

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over $[-K, K]$ and take K to be large.

[11]To see this, observe that $\bar{\ell} (\theta) > 1$ and the properties of v (i.e. $v_{ll} \leq 0$), imply that $\lambda + v_l \left(\theta, \bar{\ell} (\theta) \right) \leq \lambda + v_l (\theta, 1)$. Furthermore, $\lambda \bar{\ell} (\theta) < v (\theta, 1) < \lambda + v (\theta, 1)$, and since $W_d = \lambda + v_l (\theta, d)$ is monotone decreasing in d (since $v_{ll} \leq 0$), it follows that $\lambda + v_l \left(\theta, \bar{\ell} (\theta) \right) < 0$.

2.2.4   Dividend policy without rollover

To highlight the interaction between dividends and rollover risk, it is useful to start by character-
izing the dividend payout of a bank that does not face a run. To this end we make the following
assumption about v,

Assumption B1. $\frac{v_\theta(\theta,l)}{v_l(\theta,l)}$ is strictly increasing in l.

The assumption ensures uniqueness of the bank failure threshold – the cutoff on the bank fun-
damentals below which banks pay out all available liquid assets as dividends (and choose not to
survive a run if there is one), and above which banks pay out only part of their liquid assets as
dividends (and choose to survive a run if there is one). We maintain this assumption throughout
the paper. The failure threshold and bank dividend policy in the absence of runs are described in
the following Proposition.

Proposition 2.1. *Consider a bank that does not face a run, i.e. $A = 0$. If $\lambda < -v_l\left(\underline{\theta}, 0\right)$, then
banks with $\theta > \underline{\theta}$ choose $d_{nr}\left(\theta\right) = d^*$, where d^* solves the first-order condition*

$$\left(\lambda + v_l\left(\theta, d^*\right)\right) d^* = 0. \tag{2.9}$$

If $\lambda \geq -v_l\left(\underline{\theta}, 0\right)$, then there is a unique cutoff $\theta^* \in \left[\underline{\theta}, \overline{\theta}\right)$, that solves

$$\lambda = -v_l\left(\theta^*, \overline{\ell}\left(\theta^*\right)\right), \tag{2.10}$$

*such that banks with $\theta \leq \theta^*$ choose $d_{nr}\left(\theta\right) = \overline{\ell}\left(\theta\right)$, and banks with $\theta > \theta^*$ choose $d_{nr}\left(\theta\right) = d^*$, where
d^* solves the first-order condition*

$$\lambda = -v_l\left(\theta, d^*\right). \tag{2.11}$$

In both cases, $d_{nr}\left(\theta\right)$ is increasing in θ.

Proof. See Appendix A.2.   □

Proposition 2.1 shows that, in the absence of runs, banks with higher portfolio quality pay
higher dividends. This outcome is a direct implication of the single crossing condition, $v_{l\theta} > 0$.
Put differently, absent runs, higher dividends constitute good news about a bank's type. This
monotonicity in dividend payouts need not be preserved in the presence of a rollover episode, as we
show below.

When the private benefits to the bank owner from paying dividends are sufficiently high ($\lambda \geq
-v_l\left(\underline{\theta}, 0\right)$), then even banks with low values of θ find it optimal to pay dividends. Since those banks
have limited liquid assets, they prefer using all available liquidity to pay out dividends. The "failure"
threshold in that case – the cutoff at which a bank switches from a corner to an interior solution is
given by θ^*. We view this particular case as the empirically-relevant one in light of our discussion

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of the risk-shifting incentives by banks in the Introduction and our interest in incorporating both risk-shifting and signaling incentives into a common framework. Therefore, for the rest of the paper we will assume that the second case in Proposition 2.1 applies.

Assumption B2. $\lambda \geq -v_l\left(\underline{\theta}, 0\right)$.

2.3 Equilibrium with two dividend levels

We start by restricting the set of dividends that a bank can choose to two levels, denoted by $d^0 = 0$ and $d^1 = m > 0$. Therefore, the bank faces a binary dividend choice – either pay a fixed positive dividend or do not pay any dividend. Later on (Section 2.4), we relax this assumption and analyze the equilibrium outcome when the bank can choose any non-negative dividend that is feasible given the bank's type.

In the two-dividend setting, we compare equilibrium outcomes under two information structures. First, we consider only the resilience effect of dividends by assuming that lenders do not observe the dividend choice of the bank and instead observe an exogenous private signal about the bank's type. We call this case the exogenous information case. Formally, lenders observe a private signal about θ, $\theta_i = \theta + \eta_i^\theta$, with $\eta_i^\theta \sim_{i.i.d.} N\left(0, \alpha_\theta^{-1}\right)$, where α_θ denotes the signal precision. We analyze this environment in Section 2.3.1.

Next, we introduce the signaling effect by assuming that lenders observe the bank's dividend and make inferences about the bank's type based on that information and their prior beliefs. Hence, the dividend choice of the bank acts as an endogenous signal about the bank's type. We additionally assume that dividends are observed by lenders with small idiosyncratic noise to abstract away from the possibility of multiple equilibria due to common certainty resulting from the observation of a public signal (as in Woodford (2003a), Myatt and Wallace (2014), Kolbin (2015), Angeletos and Lian (2016a), or Gaballo (2016)).[12] Formally, lenders observe a private signal about dividends, $d_i = d\left(\theta\right) + \eta_i^d$, with $\eta_i^d \sim_{i.i.d.} N\left(0, \alpha_d^{-1}\right)$, where $d\left(\theta\right)$ is the dividend choice of a bank with type θ, and α_d denotes the signal precision. We analyze this environment in Section 2.3.2.

2.3.1 Exogenous information and the resilience effect

First, we consider the exogenous information case where dividends are not observed by lenders and serve no signaling role. In this case a dividend payout has a direct negative effect on bank survival. We consider equilibria in monotone strategies by lenders, i.e. lenders attack iff their signal $\theta_i \leq \hat{\theta}$. In addition, the bank's problem is characterized by a failure cutoff θ_f, such that a bank with quality $\theta < \theta_f$ fails the rollover episode and a banks with quality $\theta > \theta_f$ survive.

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[12]See Angeletos and Lian (2016b) for a survey of the implications of relaxing the assumption of common knowledge of agents' information sets in environments with coordination. In addition to its technical role, we can interpret the private noise in dividend observations as a reduced-form for limited attention by some lenders (Sims (2003), Myatt and Wallace (2012)).

Given the distribution of signals and a monotone strategy summarized by the (strategic) cutoff $\hat{\theta}$, the fraction of lenders running is given by

$$A\left(\theta, \hat{\theta}\right) = \Phi\left(\sqrt{\alpha_\theta}(\hat{\theta} - \theta)\right). \tag{2.12}$$

Clearly, $A_\theta < 0$, so bank with higher fundamentals face a run of a smaller size. We make the following additional technical assumption.

Assumption A1: $m < p$.

Assumption A1 ensures that the failure cutoff θ_f is unique given a binary dividend choice for the bank. We show below that a bank at the failure cutoff will face a run of size p. Assumption A1, thus, restricts the dividend payout that a bank can make to be smaller than the smallest liquidity outflow that a failing bank suffers.[13]

Proposition A.1 in Appendix A.1 shows that there is a unique equilibrium in monotone strategies, and that this is the unique equilibrium of the rollover game. Given the discrete choice set for dividends, there are two cases to consider when characterizing the equilibrium. Importantly, the structure of the equilibrium depends on how high the utility of paying dividends is. Formally, let $\tilde{\theta} \equiv \bar{\ell}^{-1}(m+p)$ denote the bank type which can just afford to pay the dividend and sustain a run of size p. The structure of the equilibrium then depends on whether $\lambda m \geq v\left(\tilde{\theta}, p\right)$ or $\lambda m < v\left(\tilde{\theta}, p\right)$. Figure 2.1 shows the equilibrium dividend payout and failure cutoff for the two cases.
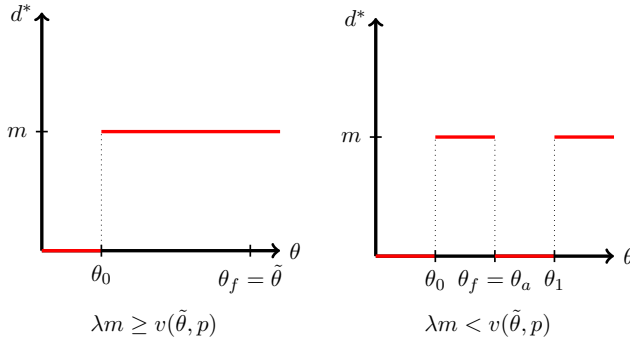
Figure 2.1: Equilibrium dividend policy and failure threshold.

If $\lambda m \geq v\left(\tilde{\theta}, p\right)$, then given a run of size p, the $t = 0$ payoff from paying a dividend for a type $\tilde{\theta}$ bank is higher than the continuation value of the bank conditional on not paying a dividend and surviving. This is also true for banks with $\theta < \tilde{\theta}$, since these banks have a strictly lower continuation

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[13]Without A1, banks with θ for which it is not feasible to pay the dividend ($\bar{\ell}(\theta) < m$) survive exogenously, as long as $A(\theta^f, \hat{\theta}) \leq \bar{\ell}(\theta)$ and, so, there may be two disjoint failure regions.

value.[14] Banks with $\theta < \tilde{\theta}$ would then pay dividends, knowing that they will fail the rollover episode and, so, $\theta_f \geq \tilde{\theta}$.

However, as in other global games models (Morris and Shin, 2003), the strategic uncertainty resulting from dispersed private information determines a run size of $A\left(\theta_f, \hat{\theta}\right) = p$ for a bank at the equilibrium failure threshold, θ_f. Therefore, it cannot be the case that $\theta_f > \tilde{\theta}$, since given the definition of $\tilde{\theta}$, there are bank types $\theta \in \left(\tilde{\theta}, \theta_f\right)$ that can both survive the run and pay out the dividend m, which contradicts the definition of θ_f. Consequently, $\theta_f = \tilde{\theta}$.

If $\lambda m < v\left(\tilde{\theta}, p\right)$, then $\theta_f < \tilde{\theta}$, since in that case a $\tilde{\theta}$ bank is better off not paying a dividend and surviving a run of size p. Furthermore, $\theta_f \leq \theta_a$, where $\theta_a \leq \tilde{\theta}$ is implicitly defined by $\lambda m = v\left(\theta_a, p\right)$.[15] Hence, θ_a denotes the type of bank that is indifferent between paying a dividend m and failing or not paying a dividend and surviving when the run is of size p. On the other hand, banks with $\theta < \theta_a$ always fail either because they prefer to pay a dividend over surviving or because they do not have sufficient resources to survive (even if they do not pay a dividend). Thus, $\theta_f = \theta_a$.

Equilibrium dividend payouts also differ across the two cases as shown in Figure 2.1. In the Figure, $\theta_0 \equiv \overline{\ell}^{-1}(m)$ denotes a bank that is just able to pay a dividend m, so paying a dividend is not feasible for banks with $\theta < \theta_0$. On the other hand, for banks with $\theta \in [\theta_0, \theta_f]$, paying a dividend is feasible but by doing so, these bank types lower the liquidity available at $t = 1$ to survive the rollover episode. Some of these bank types cannot survive even if they do not pay a dividend (e.g. bank types sufficiently close to θ_0). However, for bank types sufficiently close to θ_f not paying a dividend ensures survival of the rollover episode. Nevertheless, these banks *choose* to fail by paying a dividend.[16]

Therefore, in the case where lenders observe exogenous signals about θ, a bank that pays out a dividend ends up unambiguously increasing the total liquidity outflow it will experience. Since a higher liquidity outflow can be met only by a bank with higher θ, having the option to pay a dividend increases the bank failure threshold in equilibrium. This is the resilience effect associated with dividend payments.

2.3.1.1   Negative dividend externality and amplification

The resilience effect implies that by paying a dividend a bank weakens its ability to survive. Therefore stronger incentives to pay a dividend, given, for example, by a higher value of λ, increase the bank failure threshold keeping the behavior of lenders unchanged. However, by paying a dividend and choosing to fail, a bank exerts a negative externality on other banks through the equilibrium response of lenders. To illustrate this, suppose that $\lambda m < v\left(\tilde{\theta}, p\right)$, so that the failure and strategic

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[14]Recall that $v_\theta > 0$.

[15]To see this, note that if $\theta_f > \theta_a$, then by the properties of v, $\lambda m < v(\theta_f, p)$, which contradicts the definition of θ_f.

[16]Whenever $\lambda m < v\left(\tilde{\theta}, p\right)$, some surviving banks choose not to pay dividends in order to ensure their survival. Only when the utility of paying dividends is sufficiently high relative to the continuation value of the bank without dividend payments will they start paying dividends. This happens at θ_1, implicitly defined by $\lambda m + v\left(\theta_1, A\left(\theta_1, \hat{\theta}\right) + m\right) = v\left(\theta_1, A\left(\theta_1, \hat{\theta}\right)\right)$.

cutoffs are jointly determined by

$$\lambda m = v\left(\theta_f, A\left(\theta_f, \hat{\theta}\right)\right). \tag{2.13}$$

and

$$\Pr\left\{\theta > \theta_f | \hat{\theta}\right\} = A\left(\theta_f, \hat{\theta}\right) = p. \tag{2.14}$$

By equation (2.14), $\frac{\partial \hat{\theta}}{\partial \theta_f} > 0$, so that if lenders anticipate that more banks (choose to) fail, they become more aggressive. Intuitively, since lenders have imperfect and dispersed information about the type of bank they are facing, a larger set of failing banks implies that the lender that is indifferent between running and rolling over must be more optimistic and thus observe a higher signal $\hat{\theta}$.

However, $A_{\hat{\theta}} > 0$, and more aggressive lenders lead to larger runs for all banks. Formally, from equation (2.13), $\frac{\partial \theta_f}{\partial \hat{\theta}} > 0$. Combining these two effects, we have that,

$$\frac{d\theta_f}{d\lambda} = \frac{\partial \theta_f}{\partial \lambda} + \frac{\partial \hat{\theta}}{\partial \lambda}\frac{\partial \theta_f}{\partial \hat{\theta}} = \frac{\partial \theta_f}{\partial \lambda} + \left(\left.\frac{\partial \hat{\theta}}{\partial \theta_f}\right|_{A\left(\theta_f, \hat{\theta}\right)=p} \frac{d\theta_f}{d\lambda}\right)\frac{\partial \theta_f}{\partial \hat{\theta}}$$

$$= \frac{\frac{\partial \theta_f}{\partial \lambda}}{1 - \left.\frac{\partial \hat{\theta}}{\partial \theta_f}\right|_{A\left(\theta_f, \hat{\theta}\right)=p} \frac{\partial \theta_f}{\partial \hat{\theta}}} > \frac{\partial \theta_f}{\partial \lambda},$$

since $\left.\frac{\partial \hat{\theta}}{\partial \theta_f}\right|_{A\left(\theta_f, \hat{\theta}\right)=p} = 1$, and $\frac{\partial \theta_f}{\partial \hat{\theta}} < 1$. Thus, a strengthening of the incentives of banks to pay dividends results in an amplified response to the bank failure threshold via the equilibrium feedback between the failure cutoff and strategic cutoff.[17]

Therefore, the resilience effect induces a negative dividend externality between banks which ends up amplifying financial instability. This negative dividend externality is conceptually different from the dividend externality in Acharya, Le, and Shin (2017), which operates through the network of inter-bank claims.

2.3.2   Endogenous information and the signaling effect

Next, we consider the case where lenders observe the dividend action of the bank and update their beliefs about the bank's type based on (a noisy signal of) that action. In this case, when lender signals are sufficiently precise, paying a dividend may actually *decrease* the total liquidity outflow that the bank experiences because of its indirect effect on the run size.

As before, we consider equilibria in monotone strategies by lenders, i.e. lenders attack iff their signal $d_i \leq \hat{d}$.[18] The bank's problem is still characterized by a failure cutoff θ_f. We characterize equilibria under several assumptions.

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[17]This amplification effect is also the reason for the two cases that one has to consider when characterizing the equilibrium. Whenever the change in λ is sufficiently large, the economy may move from the $\lambda m < v\left(\tilde{\theta}, p\right)$ to the $\lambda m \geq v\left(\tilde{\theta}, p\right)$ case, with the failure threshold changing discretely from θ_a to $\tilde{\theta}$.

[18]Proposition 2.2 below shows that under some conditions, this restriction is without loss of generality.

Assumption A1': $m < \frac{1}{2}$.

Assumption A2. $\Pr\left\{\theta \in \left(\underline{\theta}, \overline{\theta}\right)\right\} < \Pr\left\{\theta < \underline{\theta}\right\} \Pr\left\{\theta > \overline{\theta}\right\}$.

Assumption A3. $p < \frac{\Pr\{\theta > \overline{\theta}\}}{\Pr\{\theta > \theta_0\}}$.

Assumption A1' is a technical condition similar to Assumption A1 above, which ensures that the bank failure threshold is unique.[19] Similarly, Assumption A3 is a technical condition which ensures that $\hat{d}$ always exists. It is a sufficient condition ensuring the existence of a marginal lender, i.e. a lender which has received a signal that makes her indifferent between running and rolling over.[20] Intuitively, the assumption puts an upper bound on how aggressive lenders are when deciding whether to roll over or run. Finally, Assumption A2 is a condition on the size of the dominance regions relative to the multiplicity region. This assumption guarantees that a higher dividend signal d_i is always good news about bank survival. The assumption implies that the dominance regions are sufficiently large relative to the multiplicity region, so that the location of the failure threshold does not change the lenders' inference.[21]

Given the distribution of signals and the cutoff strategies of lenders, the fraction of lenders running is given by

$$A\left(d, \hat{d}\right) = \Phi\left(\sqrt{\alpha_d}(\hat{d} - d)\right) \tag{2.15}$$

Therefore, $A_d < 0$, so a higher dividend is associated with a lower run size. This dependence of the run size on the dividend is what we call the signaling effect.

To characterize equilibria, note, as in the previous section, that the binary dividend choice implies that the structure of the equilibrium may differ depending on parameter values. Two Lemmas given in Appendix A.1 (Lemmas A.1 and A.2) characterize the bank's and lenders' problems. Here we briefly summarize the main insights.

First, suppose that $m + A(m, \hat{d}) > A(0, \hat{d})$, so the liquidity outflow given a dividend payment is higher than the outflow given no dividend payment. In this case the signaling effect is weak and the resilience effect dominates. The liquidity outflow of paying dividends relative to not paying dividends is as in the exogenous information case – higher dividends unambiguously worsen the bank's liquidity position. Thus, as in the exogenous information case, the bank faces a trade-off between paying a dividend and surviving the rollover episode.

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[19]Specifically, it ensures that $m \leq \overline{\ell}(\theta)$ whenever $A(0, \hat{d}) \leq \overline{\ell}(\theta)$. If $A(0, \hat{d}) < \overline{\ell}(\theta)$, while $m > \overline{\ell}(\theta)$, some banks for which it is not feasible to pay the dividend survive exogenously.

[20]In the limit, as $\alpha_d \to \infty$, one needs a weaker condition to ensure this. In particular, having $p < 1$ is sufficient in that case.

[21]If A2 does not hold, it may be the case that how a higher dividend signal is interpreted by lenders (whether as good or bad news about bank survival) may depend on the position of the bank failure threshold in the multiplicity region. As a result there may be multiple equilibria similar to Angeletos, Hellwig, and Pavan (2006). In that case, the results of this section will apply to the equilibrium in which a higher dividend signal is interpreted by lenders as good news for bank survival. A less restrictive and more easily satisfied condition for monotone inference of lenders is needed in the case where dividends are not restricted to one of two levels (see Section 2.4).
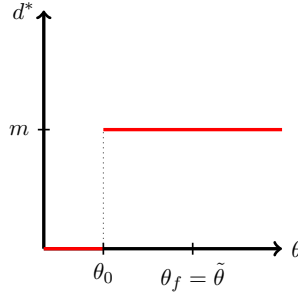
Figure 2.2: Dividend policy and failure threshold with strong signaling effect.

Similar to the exogenous information case, let $\tilde{\theta} \equiv \bar{\ell}^{-1}\left(m + A\left(m, \hat{d}\right)\right)$. Suppose that $\lambda m \geq v\left(\tilde{\theta}, A(0, \hat{d})\right)$, so that a bank of type $\tilde{\theta}$ which can just afford to both pay a dividend and survive a run of size $A\left(m, \hat{d}\right)$ is better off paying the dividend. In that case, as in the exogenous information case, $\theta_f = \tilde{\theta}$. Furthermore, banks with $\theta \in \left[\theta_0, \tilde{\theta}\right]$ pay the dividend and fail. Conversely, if $\lambda m < v\left(\tilde{\theta}, A(0, \hat{d})\right)$, then $\theta_f = \theta_a$, which solves $\lambda m = v\left(\theta_a, A(0, \hat{d})\right)$, and some banks with $\theta > \theta_f$ choose to not pay a dividend and survive. Therefore, the dividend payout and failure threshold are similar to those in Figure 2.1.

Next, suppose that $A(m, \hat{d}) + m \leq A(0, \hat{d})$. Then the liquidity outflow from paying a dividend is *lower* than the liquidity outflow from not paying a dividend. In this case the signaling effect is strong and dominates over the resilience effect, so that there is no longer a trade-off for the bank between paying a dividend and surviving the run. Hence, if a bank can pay the dividend it would always do so, and the only failing banks in this case are either banks for which paying the dividend is not feasible (i.e. banks with $\theta < \theta_0 \equiv \bar{\ell}^{-1}(m)$) or banks which can pay the dividend but do not have enough liquidity to survive. Therefore, $\theta_f = \tilde{\theta} = \bar{\ell}^{-1}\left(m + A\left(m, \hat{d}\right)\right)$. The dividend payout and failure threshold in that case are as shown in Figure 2.2.

Whether the signaling effect is weak or strong depends on how coordinated lenders are, which depends on the idiosyncratic signal precision α_d. When α_d is sufficiently high, the signaling effect dominates the resilience effect and paying a dividend ends up lowering the liquidity outflow from the bank, i.e. $A(m, \hat{d}) + m < A(0, \hat{d})$. Also, if the signaling effect is sufficiently strong for sufficiently large values of α_d, the equilibrium in monotone strategies is the unique equilibrium of this economy, as we show in the next proposition.

Proposition 2.2. *(Dividend signaling equilibrium) Consider the endogenous information model, in which lenders follow a monotone strategy with cutoff $\hat{d}$, and banks fail according to a cutoff θ_f. Suppose that assumptions A1', A2, and A3 hold. Then, there is an $\overline{\alpha} > 0$, such that for $\alpha_d > \overline{\alpha}$, $\hat{d}$,*

and θ_f are uniquely determined by

$$\hat{d} = \frac{m}{2} + \frac{1}{\alpha_d m} \log \left(\frac{p \Pr \{\theta < \theta_0\}}{\Pr \{\theta > \theta_f\} - p \Pr \{\theta > \theta_0\}} \right), \tag{2.16}$$

and

$$\theta_f = \bar{\ell}^{-1} \left(m + A \left(m, \hat{d} \right) \right), \tag{2.17}$$

and a bank pays a dividend iff $\theta \geq \theta_0 = \bar{\ell}^{-1}(m)$. Furthermore, the unique monotone strategy equilibrium is also the unique equilibrium of this economy.

Proof. See Appendix A.2.   □

To further clarify that a higher α_d strengthens the signaling effect, consider the following comparative static result.

Proposition 2.3. *(Stronger signaling effect). For sufficiently high α_d, θ_f is decreasing in α_d.*

Proof. See Appendix A.2.   □

A higher value of α_d ends up decreasing the liquidity outflow $m + A\left(m, \hat{d}\right)$ associated with paying a dividend. Intuitively, when α_d is larger, lenders are more coordinated and the dividend choice influences the actions of a larger group of lenders. Thus, a bank at the failure threshold that has just enough liquidity to meet the liquidity outflow associated with paying a dividend and survive a run by $A\left(m, \hat{d}\right)$ lenders has strictly more liquidity when α_d is increased, so that even weaker banks can now survive. As $\alpha_d \to \infty$, lenders become almost perfectly coordinated and the signaling effect becomes extremely powerful as we show next.

Proposition 2.4. *Suppose that assumptions A1' and A2 hold and that $p < 1$. In the limit, as $\alpha_d \to \infty$, $\theta_f \to \theta_0 = \ell^{-1}(m)$ and $\hat{d} \to \frac{m}{2}$.*

Proof. See Appendix A.2.   □

In the limit, when lenders receive arbitrarily precise signals and, so, are almost perfectly coordinated, paying a dividend leads to a liquidity outflow equal only to that dividend payment. Consequently, all banks for which it is feasible to pay the dividend do so and survive. Figure 2.3 illustrates the equilibrium dividend policy and failure threshold in this limiting case.

2.4 Unrestricted dividend choice

In this section we relax the assumption of binary dividend choice and instead assume that a type θ bank can choose any dividend $d \in [0, \bar{l}(\theta)]$. We assume that lenders have a uniform prior about θ over $[-K, K]$ for $K > 0$.[22] As in Section 2.3.2, lenders observe the bank's dividend d with normally

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[22]We choose K to be sufficiently large, so that the lenders' inference is monotone in their signals, i.e. lenders will essentially have an improper prior over the real line. See Lemma A.7 in Appendix A.3 for details.
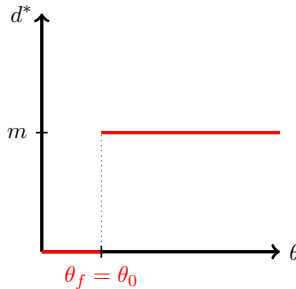
Figure 2.3: θ_f and dividend policies as $\alpha_d \to \infty$

distributed idiosyncratic noise with precision α_d. Below we present only the main insights from relaxing the two-dividend assumption. The details of the analysis are contained in Appendix A.3.
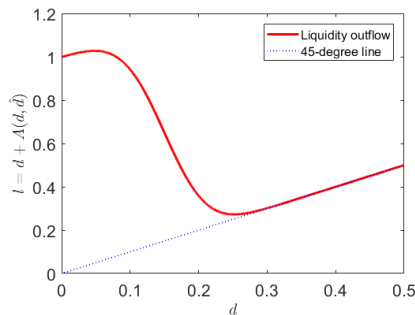
Figure 2.4: Liquidity outflow $\left(d + A\left(d, \hat{d}\right)\right)$ as a function of dividends paid.

We again restrict attention to equilibria in monotone strategies, in which a lender refuses to roll over if $d_i < \hat{d}$, for some $\hat{d} \in \mathbb{R}$.[23] With normally distributed dividend signals and monotone strategies, the fraction of agents attacking given $\hat{d}$, is

$$A(d\left(\theta\right), \hat{d}) = \Phi(\sqrt{\alpha_d}(\hat{d} - d\left(\theta\right))). \tag{2.18}$$

It is useful to define $d_{\min}$ as the solutions to

$$1 + A_d\left(d, \hat{d}\right) = 0, \tag{2.19}$$

such that $\hat{d} < d_{\min}$. In addition, we consider economies with $\hat{d} \in (0, 1)$ and α_d sufficiently large, so that $d_{\min} > 0$ is the minimizer of $d + A\left(d, \hat{d}\right)$.[24] In that case, as Figure 2.4 shows, the liquidity

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[23]Proposition A.2 in Appendix A.3 shows conditions under which that restriction is without loss of generality.

[24]Conditions B3 and B4 in Appendix A.3 ensure that in any monotone strategy equilibrium of this economy,

outflow that a bank experiences is decreasing for some values of d, so that the signaling effect dominates the resilience effect. A decreasing liquidity outflow plays an important role in the optimal dividend payout decision of banks as we show next.

Lemma 2.1. *Suppose that lenders follow a monotone strategy with cutoff at $\hat{d}$. Then there is a unique critical threshold over bank fundamentals given by θ_f, such that banks with $\theta < \theta_f$ fail and banks with $\theta > \theta_f$ survive. Furthermore, θ_f satisfies*

$$\lambda \bar{\ell}(\theta_f) = \lambda d^*(\theta_f) + v\left(\theta_f, d^*(\theta_f) + A\left(d^*(\theta_f), \hat{d}\right)\right), \tag{2.20}$$

where $d^*(\theta) > d_{\min}$ satisfies the condition

$$\frac{\lambda}{1 + A_d\left(d^*(\theta), \hat{d}\right)} = -v_l\left(\theta, d^*(\theta) + A\left(d^*(\theta), \hat{d}\right)\right). \tag{2.21}$$

The bank's optimal dividend policy is given by

$$d(\theta) = \begin{cases} \bar{\ell}(\theta) & , \ \theta < \theta_f \\ \{\bar{\ell}(\theta), d^*(\theta)\} & , \ \theta = \theta_f \\ d^*(\theta) & , \ \theta > \theta_f \end{cases} . \tag{2.22}$$

Proof. See Appendix A.2. $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\square$

It is instructive to compare the optimal dividend choice of the bank in this case to the case when there is no run ($d_{nr}(\theta)$ given by equation (2.11)). First, if the bank chooses to survive, Lemma 2.1 implies that it might have to distort its dividend payment above the no-run dividend level, $d_{nr}(\theta)$. This is specifically the case for banks with θ for which $d_{nr}(\theta) \leq d_{\min}$. These banks do not want to be on the downward sloping segment of the liquidity outflow schedule, $l(d) = d + A\left(d, \hat{d}\right)$. Since a higher dividend is associated with a lower liquidity outflow in that segment, they optimally choose a dividend of at least $d_{\min}$. Intuitively, such banks have strong incentives to distort their dividends upward and pay a dividend similar to higher-quality banks to help more lenders coordinate on rolling over.

In addition, the marginal impact on the size of the run given by $A_d\left(d, \hat{d}\right)$, decreases strongly in d around $d_{\min}$. Intuitively, since the lenders care about whether the bank fails or survives the rollover episode (rather than the specific bank type), the dividend payouts of banks with higher fundamentals are already interpreted by most lenders as strong evidence that the bank will survive the rollover episode, so any upward distortion in dividends has only a small effect on lenders' inference.

$\hat{d} \in (0, 1)$, while the observation that $d_{\min} \to \hat{d}$ and $A\left(0, \hat{d}\right) \to 1$ as $\alpha_d \to \infty$ ensure that $d_{\min} + A\left(d_{\min}, \hat{d}\right) \leq A\left(0, \hat{d}\right)$ for sufficiently large α_d. Focusing on economies in which $\hat{d} \in (0, 1)$ is the most interesting given the assumption on feasible dividend payouts for banks at the lower and upper dominance thresholds.
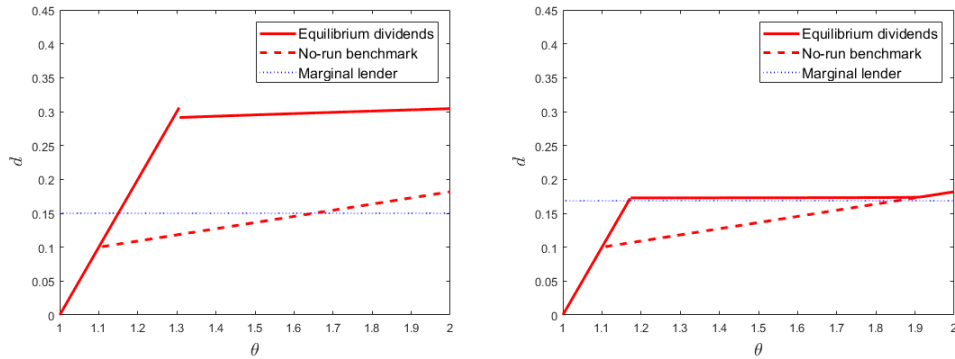
Figure 2.5: Equilibrium dividend policies for low (left panel) and high (right panel) dividend signal precisions. Parametric assumptions: $v(\theta, l) = \theta \ln(\theta - l)$, for $1 \leq \theta < 2$ (multiplicity region); $p = 0.5$, $\lambda = 1.1$. $\sigma = 0.05$ for the left panel and $\sigma = 0.001$ for the right panel.

By equation (2.21), the combination of these two effects implies that banks which distort their dividends relative to the no-run level end up choosing payouts around $d_{\min}$. Hence, as in the two-dividend case, the strong signaling effect lowers the sensitivity of dividends to the bank fundamentals relative to their dividend payout in the absence of rollover and, so, banks with different fundamentals choose similar dividends.

Figure 2.5 illustrates this feature by showing the (equilibrium) dividend policy of banks for one particular example.[25] The figure plots the equilibrium dividend policies (solid line), as well as the dividend policies in the no-run case (dashed line) for banks in the multiplicity region. Banks below the failure threshold liquidate all assets and pay them as dividends. Otherwise, banks pay a dividend that is higher than their no-run dividend. Furthermore, the dividends of surviving banks are more compressed and vary less with θ relative to the no-run case. As the signal precision is increased and the signaling effect is strengthened (Figure 2.5 (right panel)), the dividend policy becomes even less sensitive to θ for banks close to the failure threshold.

Turning to equilibrium characterization, Proposition A.2 in Appendix A.3 characterizes equilibria in monotone strategies for this economy. It shows that if the equilibrium in monotone strategies is unique, it is the unique equilibrium of this economy. Similar to the two-dividend case, equilibrium uniqueness in this case results from the combination of sufficiently large dominance regions together with the monotonicity of bank actions when there is no coordination problem among lenders (by the single-crossing assumption $v_{l\theta} > 0$). Specifically, banks with very low values of the fundamental always pay lower dividends compared to banks with very high fundamentals, *irrespective* of the actions of lenders and the inferences they make about θ from the dividend level they observe. Thus, very low (high) private signals are always interpreted as bad (good) news about θ, regardless of

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[25]See Appendix A.3 for details on the example.

the actions of lenders with intermediate signals or the dividend policies of banks with intermediate values of θ. Therefore, despite being endogenous, the information structure of lenders always has this property.

In addition to equilibrium characterization, we can show the following stark result for the limiting case when lender signals become arbitrarily precise.

Proposition 2.5. *In the limit, as $\alpha_d \to \infty$, there is a unique equilibrium with $\theta_f \to \theta^*$, where θ^* solves $\lambda = -v_l\left(\theta^*, \bar{\ell}\left(\theta^*\right)\right)$, $\hat{d} \to \bar{\ell}\left(\theta^*\right)$. Furthermore, the bank's dividend policy, $d\left(\theta\right) \to d_{nr}\left(\theta\right)$, $\forall \theta$.*

Proof. See Appendix A.2. □

As in Proposition 2.4, the reason for this stark result is the extreme strengthening of the signaling effect. As $\alpha_d \to \infty$, lenders become perfectly coordinated and, so, $A\left(d, \hat{d}\right) \to 0$ for $d > \hat{d}$. However, since a bank that chooses to survive always selects a dividend $d^* > d_{\min} > \hat{d}$, it follows that $A \to 0$ for any surviving bank, including for a bank with type θ_f. This, however, can only be consistent with indifference between survival and failure if $\theta_f = \theta^*$.

Figure 2.5 provides an illustration of how a strengthening of the signaling effect ends up influencing the equilibrium away from this limit. More precise dividend signals reduce the failure threshold and bring it closer to the no-run failure threshold. Intuitively, more precise dividend signals imply that lenders are more coordinated. As a result, the marginal bank that is indifferent between failing and surviving for a lower signal precision now faces a smaller run in case of survival, making it strictly better off from surviving. Additionally, $d_{\min}$ decreases, which further reduces the cost associated with having to distort dividends away from the no-run level, in order to survive the run.[26]

One interesting implication of the limiting case, which is suggested by the behavior of the equilibrium dividend schedules in Figure 2.5, is that in the limiting case of arbitrarily precise lender signals, $d^{*\prime}\left(\theta_f\right) \to 0$. Therefore, around the failure threshold, surviving banks pool on dividend issuance.[27] Hence, while in the two-dividend case in Section 2.3, surviving banks are forced to pool on a positive dividend payout, when dividend payouts are unrestricted, banks close to the failure threshold endogenously choose to (approximately) pool in equilibrium.

2.5 Policy implications

The possibility that banks can influence the coordination-based run they face during a period of financial market stress via their dividend choices has important implications for dividend regulation

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[26]These direct effects ends up dominating any indirect effects arising from changes in the marginal lender. In fact, as Proposition 2.5 suggests, for sufficiently high signal precision, changes in the marginal lender, $\hat{d}$, should reinforce these effects on θ_f.

[27]The intuition for this pooling result is the following. When lenders observe very precise signals, to have a marginal lender who observes a signal $\hat{d}$ *lower* than the dividend payout of all surviving banks be indifferent between running and rolling over, it must be the case that the set of surviving banks issuing a dividend close to $\hat{d}$ is relatively large in equilibrium. Thus, a large set of banks must be paying dividends close to $\hat{d}$. As signals become arbitrarily precise, having an equilibrium marginal lender with these properties entails that surviving banks close to the failure threshold pool on dividend issuance, which is ensured by $d^{*\prime}\left(\theta_f\right) \to 0$.

aimed at improving financial stability. In particular, suppose that a policy maker cares about minimizing the set of banks experiencing a coordination-based run (i.e. minimizing the failure cutoff θ_f). Consider the economy from Section 2.4 and suppose that lenders' idiosyncratic signals are arbitrarily precise ($\alpha_d \to \infty$). We analyze the effects of two dividend regulation policies in this environment – a full restriction on dividend payments and a tax on dividends.

Fully restricting dividend payments has been proposed as a macroprudential tool for stabilizing the financial system (Goodhart, Peiris, Tsomocos, and Vardoulakis, 2010a). In our framework, if banks are restricted from paying dividends, lenders have to only rely on their prior beliefs, which leads to multiple equilibria, in which the bank failure threshold can lie anywhere in the multiplicity region $\left(\underline{\theta}, \overline{\theta}\right)$. Given Proposition 2.5, this means that the bank failure threshold could be either higher or lower in that case compared to the case without restricting dividends. For a more precise comparison, suppose that restricting bank dividends and the information available in them causes the direct acquisition of private information about the bank's fundamental by market participants (e.g. as in He and Manela (2016), Szkup and Trevino (2015), or Ahnert and Kakhbod (2016)).

Proposition 2.6. *Consider the case with a continuum of dividend levels and arbitrarily precise dividend signals ($\alpha_d \to \infty$). Suppose that a policy that restricts dividend payments by banks to $d = 0$, $\forall\theta$, induces private information acquisition about θ by market participants. Then the bank failure threshold is lower with a restriction on dividends than without a restriction, iff $\theta^* > \tilde{\theta}_f$, where θ^* solves $\lambda = -v_l\left(\theta^*, \overline{\ell}\left(\theta^*\right)\right)$ and $\tilde{\theta}_f = \overline{\ell}^{-1}\left(p\right)$.*

Proof. See Appendix A.2.   □

There are two forces that drive a bank's dividend decisions in our model. On the one hand, in the absence of runs, the risk-shifting incentives associated with a high private payoff from dividends (a higher λ) lead to a failure threshold of θ^*. The higher is λ – the marginal value that the bank (owner) derives from paying one more unit of dividends – the higher is θ^*. On the other hand, without the ability to utilize the signaling effect of dividends, a bank is subject to a coordination-based run, which leads to a failure threshold of $\tilde{\theta}_f$. The higher is p – the parameter governing the strength of lenders' incentives to run – the higher is $\tilde{\theta}_f$.

Thus, if corporate governance issues are of less concern for immediate financial stability compared to the financial stress due to a coordination-based rollover crisis (i.e. λ is low, relative to p, so that $\theta^* < \tilde{\theta}_f$), restricting dividends leads to a higher bank failure threshold. On the other hand, if coordination-based runs are not of concern in a crisis episode, and corporate governance issues are particularly salient in that case (i.e. λ is high relative to p, so that $\theta^* > \tilde{\theta}_f$), then restricting dividends leads to a lower bank failure threshold.

Therefore, the effect of dividend restrictions is *ambiguous*. In contrast, a (proportional) tax on dividends *unambiguously* decreases the bank failure threshold, as we show in the next Proposition.

Proposition 2.7. *Consider the case with a continuum of dividend levels and arbitrarily precise dividend signals (i.e. $\alpha_d \to \infty$). In that setting, a higher proportional tax on dividend payments, $\tau \in (0, 1)$, decreases the bank failure threshold θ_f.*

Proof. See Appendix A.2.   □

It may be *a priori* unclear to a policy maker whether corporate governance or coordination-based runs are more important in a period of financial stress, so that the sign of comparison between θ^* and $\tilde{\theta}_f$ is not clear. In that case, Proposition 2.7 suggests that a policy maker can instead use a tax on dividend payments. Such a tax induces banks to adjust their risk-shifting behavior, so that corporate governance concerns are alleviated. In addition, the tax does not distort the signaling effect of dividends, which has a powerful effect on the coordination-based run.[28]

2.6   Empirical relevance

We now discuss the empirical relevance of our theory. One implication of our model is that the combination of rollover risk and a strong signaling effect may lead to a lower sensitivity of dividends to a change in fundamentals compared to an environment in which rollover risk is absent (Section 2.4). Second, signaling should be associated with a negative relation between dividend payments and short-term funding outflows. Finally, the impact of a change in dividends on short-term funding outflows increases in the strength of the signaling effect. Below we document three novel empirical facts and discuss related empirical work that is broadly consistent with these predictions.[29]
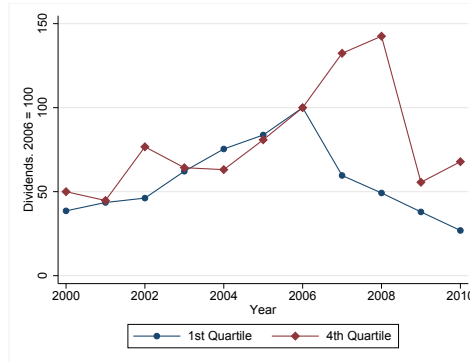
Figure 2.6: Yearly nominal dividend payments for large U.S. banks with different reliance on short-term debt. Source: Bank holding companies Y-9C reports. Large bank are defined as bank holding companies with more than $500 million in assets as of Q1-2006. Banks holding companies are grouped into four quartiles based on their short-term debt relative to total liabilities in 2006. The figure compares the dividend payments of the 1st and the 4th quartile. Short-term debt is defined as the sum of repurchase agreements and federal funds.

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[28]Notice that a tax on dividends also works to correct for any negative externalities arising from a bank's dividend payments beyond correcting for spillovers between bank equity and debt holders. For example, suppose that the marginal social benefit from paying a dividend is $\lambda^S < \lambda$, for example, because banks do not internalize the effects of their actions for financial stability through other channels than the ones emphasized in our paper. In that case, setting $\tau = \frac{\lambda}{\lambda^S} - 1$ aligns the bank's incentives with those of the policy maker.

[29]Additional information on data and measurement are included in Appendix A.4.

Consistent with the first implication, we show that banks that relied more heavily on short-term funding prior to the crisis were more reluctant to cut dividends during the crisis. Specifically, we rank U.S. banks according to the share of liabilities in short-term debt (defined as the sum of federal funds and repurchase agreements) in 2006 and examine the behavior of banks in the first and fourth quartiles. Figure 2.6 plots the dividend payments of these two groups of banks. While both groups have similar trends in dividend growth before 2007, their dividend payments diverge sharply thereafter. Banks that relied relatively less on short-term debt decreased their dividend payments starting in 2007. In contrast, banks that relied relatively more on short-term debt stayed on their pre-2007 dividend growth trend during 2007 and 2008.[30]
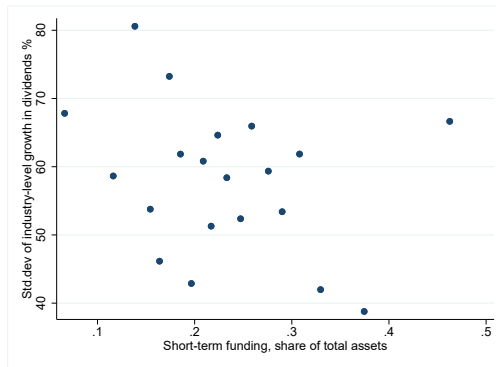
Figure 2.7: Industry level standard deviation of dividend growth and average share of short-term debt relative to total assets, 2005-2016 (binned scatter plot). Source: CRSP and Compustat. Short-term debt defined as current liabilities. Industry correspond to 4-digit SIC code, excluding financials (SIC codes 6000-6999) and utilities (SIC codes 4900-4949).

Second, and again consistent with the first implication, we show that industries in which firms rely relatively more on short-term funding also have more stable dividend payments.[31] Figure 2.7 plots the standard deviation of dividend growth against the average share of short-term debt relative to assets for different U.S. industries. As the figure shows, there is a negative relation between these two quantities.

Third, and consistent with the second implication of our theory, we show that banks that cut dividends less during 2007-2009 also faced a lower outflow of short-term funding during the crisis. Figure 2.8 plots the percentage change in dividend payments for individual banks (relative to the mean change across all banks) against the percentage change of repurchase agreement liabilities during that period. There is a strong positive relationship between dividend changes and the change in repurchase agreements during that period.

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[30]Including the 2nd and the 3rd quartile would show a similar pattern, with quartile three being slower to cut dividend payments relative to quartiles one and two.

[31]Our theoretical analysis naturally carries over to industries beyond the banking sector where firms also face coordination based runs from short-term lenders.
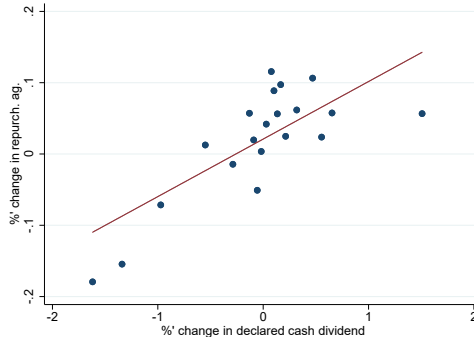
Figure 2.8: Symmetric changes in dividends and changes in repurchase agreement liabilities. 2007-2009. Relative to year mean (binned scatter plot). Source: Bank holding companies Y-9C reports.

Finally, the strength of the signaling effect in our model depends on the precision of lender signals. The higher this precision, the more coordinated are lenders and the larger their aggregate response to changes in dividends. One interpretation of the noise in lender signals is that it is a reduced-form representation for limited attention by some lenders (Sims (2003), Myatt and Wallace (2012)). According to this interpretation, more precise signals reflect lenders who are more attentive to changes in the bank's dividends. Given this interpretation, the signaling effect should be stronger for banks that face more attentive lenders. Recent empirical work by Forti and Schiozer (2015) provide suggestive evidence for such a link. Specifically, the authors show for a sample of Brazilian banks that banks with more informationally-sensitive depositors such as institutional investors were more likely to increase their dividends during the 2007-2008 financial crisis.

2.7   Concluding comments

U.S banks paid large amounts in dividends during the financial crisis. In our paper we study a framework that incorporates two distinct views of the underlying reasons for this behavior – risk shifting and signaling. When signaling incentives are weak, paying dividends lowers a bank's resilience to rollover crises. However, the bank also exerts a negative externality on other banks through the rollover actions of lenders. In contrast, when changes in dividends affect the behavior of short-term lenders, lowering dividends may worsen a bank's ability to survive the rollover crisis.

The signaling effect and related reluctance of banks to cut dividends due to an increased risk of a rollover crisis may also explain why banks were reluctant to issue new equity (essentially a negative dividend) during the financial crisis (Bigio, 2012). Examining the implications of new equity issuance in an environment with rollover crises is a potentially important extension of our framework that we leave for future research.

Chapter 3

Information quality and regime change: Evidence from the lab

with Leif Helland, Felipe Iachan and Plamen T. Nenov

3.1   Introduction

Global coordination games of regime change are commonly used to analyze important economic phenomena involving elements of coordination, such as currency crises (Morris and Shin, 1998) and bank runs (Rochet and Vives (2004), Goldstein and Pauzner (2005)). An important question in this literature – both from an applied and a more theoretical perspective – is how information quality affects regime stability.

In this paper, we provide an experimental test of how changes in private information precision affect regime stability. In particular, we consider a global coordination game in which agents receive private signals with a certain precision and the payoff structure is such that a lower signal precision makes agents more likely to attack in equilibrium, decreasing regime stability.[1]

Specifically, we let subjects play a series of games where they take binary decisions – attack or not attack. Their payoff from attacking depends both on an underlying state and on the actions of others. If a sufficient number of agents chooses to attack (given the value of the underlying state), then all attacking agents obtain a discretely higher payoff. In addition, the higher the value of the state, the higher the discrete payoff from a successful attack.[2] Finally, agents have an (uninformative) uniform prior and obtain private signals about the underlying state with some dispersion. We set up the payoffs of agents to correspond to the literature on speculative currency attacks, where theory predicts that more dispersed information is destabilizing (Heinemann and

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[1]In general, the effect of a change in private information precision on regime stability is ambiguous and depends on the payoff structure that is generated by the underlying economic environment (Iachan and Nenov, 2015). To provide a clear theoretical prediction to test in laboratory settings we opt for a specific payoff structure that leads to the aforementioned comparative static.

[2]Therefore, a higher state in our abstract game can be interpreted as a lower value of a common economic fundamental.

Illing (2002), Iachan and Nenov (2015)).

In this setting we compare subjects' behavior in two treatments, one where private information dispersion is low ("Low Noise treatment") and one where the information dispersion is high ("High Noise treatment").

Our experimental results run counter to the baseline theoretical predictions. Focusing on the differences in average estimated strategic cutoffs, the comparative statics seem to go opposite of what theory predicts. More dispersed information makes agents more, not less, cautious. While relatively large variation in estimated strategic thresholds within treatments implies that we cannot reject the null of no treatment effect we are able to reject the null of observed differences corresponding to those predicted by the standard global games framework.

Motivated by this finding, we augment the standard set-up to include agents with limited depths of reasoning. In particular, we focus on one specific non-equilibrium theory that has received recent experimental and theoretical attention in the literature on global games and informational frictions (Kneeland (2016), Angeletos and Lian (2017)), namely level-k thinking (Nagel, 1995; Stahl and Wilson, 1995).[3] Models of level-k thinking assume that agents have limited depths of reasoning and, at the same time, provide additional assumptions on the agents' belief hierarchies. We show that this departure from rational expectations equilibrium potentially alters the prediction of the theory of global games substantially. Specifically, the effect of more dispersed information on regime stability will, in the presence of level-k agents, depend both qualitatively and quantitatively on what assumptions are being made about the least sophisticated agents ("L0-types") and the levels of reasoning of the majority of agents playing the game.[4]

If L0-types are sufficiently aggressive and the majority of agents engage in only a few levels of reasoning, more dispersed information tends to reduce their willingness to attack. This, in turn, makes all other types less willing to attack. Through this mechanism, increased information dispersion is stabilizing rather than destabilizing. If, on the other hand, L0-types are sufficiently passive or the majority of agents engage in multiple levels of reasoning, the effect of more dispersed information on regime stability is consistent with the predictions from equilibrium theory.[5]

Motivated by these observations, we follow Kneeland (2016) and estimate the fractions of various level-k types in our experiment on data from each of our two treatments. In addition, rather than holding their behavior fixed as in Kneeland (2016), we estimate the implied strategies of L0-types that other types respond to.[6]

Our estimates indicate that initially L0-types are perceived to be relatively aggressive. 71 percent of our subjects are classified as L1 and L2 types in the low noise treatment while the corresponding number is 55 percent in the high noise treatment. These percentages indicate that the level-k

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[3]See also Farhi and Werning (2017) for a macroeconomic application of this concept. An overview of models and evidence of non-equilibrium strategic thinking is provided in Crawford, Costa-Gomes, and Iriberri (2013).

[4]L0-types are agents that completely disregard the strategies of other players.

[5]Introducing level-k types also affects the size of the comparative statics. If L0-types are of an intermediate type, then the effects of more dispersed information are muted.

[6]There are no L0-types in our behavioral model but what more sophisticated types think about their opponents behavior is important for final outcomes.

theory is important in terms of understanding subject behavior in our experiment. According to the parameter estimates from the initial periods of play, the regime indeed becomes *more* stable if information dispersion increases, consistent with the observed differences in estimated strategic thresholds.[7]

Literature review   Initial coordination experiments focused on static games with complete information (Cooper, DeJong, Forsythe, and Ross (1990, 1992); Straub (1995); Van Huyck, Battalio, and Beil (1990)). Such games have multiple equilibria and strategic uncertainty comes to the forefront. As a response to this indeterminacy, the theory of global-games was developed by Carlsson and Van Damme (1993). The theory was later advanced by Morris and Shin (1998) to macroeconomic applications. The global games framework provides an explicit model of strategic uncertainty. It shows that coordination games with multiple equilibria under complete information may have a unique equilibrium if certain parameters of the payoff function are private information instead of common knowledge.

Heinemann, Nagel, and Ockenfels (2004) is the experimental paper closest to ours. It tests the predictions of the theory of global-games in a setting where the net payoff from a successful attack is increasing in the underlying fundamental. In a global-games equilibrium agents use monotone threshold strategies. Heinemann, Nagel, and Ockenfels (2004) document that subjects tend to use such strategies, both under public and private information. Widespread use of monotone, or near monotone, threshold strategies has also been documented in a broader class of global games experiments (Cornand and Heinemann (2014); Szkup and Trevino (2017); Avoyan (2018)).[8] Our experimental results are in line with these findings.

When the net payoff of a successful attack is increasing in the fundamentals, more precise private information should induce agents to become more cautious (i.e. increase their attack threshold) in a global-games equilibrium. The literature, however, seems to document the opposite. Heinemann, Nagel, and Ockenfels (2004) compare behavior under complete information to behavior under incomplete information.[9] They find that subjects behave more cautiously under incomplete information. Cabarales, Nagel, and Armenter (2007) test the global-games theory in a series of two persons games with a simplified information structure. The design ensures that equilibrium is reached after only four rounds of elimination of (interim) strictly dominated strategies. They find that subjects converge to the unique global games equilibrium under incomplete information, but that subjects behave less cautiously under complete information. In the main treatments of Szkup and Trevino (2017) the precision of the private signal is endogenous, in that agents face a menu of costly signals they select from prior to taking actions. They investigate a two player game similar to Carlsson

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[7]However, over time, agents behave closer to what is predicted by equilibrium theory, which suggests that there are some learning effects associated with non-equilibrium play.

[8]Heinemann, Nagel, and Ockenfels (2009) develops a method to measure strategic uncertainty as an alternative to varying the parameters of the game exogenously. They also find widespread use of threshold strategies. Heggedal, Helland, and Joslin (Forthcoming) find widespread use of threshold strategies in a coordination game with type uncertainty rather than uncertainty about fundamentals.

[9]In line with Heinemann, Nagel, and Ockenfels (2004) we view complete information as the limiting case where signal noise goes to zero and the global games selection is the prediction.

and Van Damme (1993). Subjects who chose more precise (and more costly) signals are shown to behave less cautiously. Furthermore, subjects over invest in precision compared to the global-games equilibrium. Finally, in a series of control treatments with fixed signal precision there seems to be a weakly hump-shaped relationship in which higher precision initially induces more caution but thereafter flattens out or even decreases. The pattern in our experimental data is one in which less precise private information induces more caution.

Cornand (2006) augments Heinemann, Nagel, and Ockenfels (2004) in two ways. Firstly, by having a treatment in which a public signal is added to the private signal, and, secondly, by having a treatment in which agents receive two private signals. She finds that agents rely more on the public than the private signal(s). Similar results are reached in Cornand and Heinemann (2014).

Avoyan (2018) finds that cheap talk reduces miscoordination, as it should do according to her extension of the global games theory. However, in her experiment, access to cheap talk does not lead to the theoretically expected reduction in attack thresholds, and subjects thereby miss out on significant welfare improvements. Shurchkov (2016) explores a structure in which an uninformed outsider is given the opportunity of making an announcement. She finds that such announcements only impact on coordination if the game has multiple equilibria. In such cases announcements serve as a powerful coordinating device inducing subjects to attack.

It is well known that dynamic play reintroduces indeterminacy in the global games model (Angeletos, Hellwig, and Pavan (2006); Chamley (2003)). Costain, Heinemann, and Ockenfels (2007) investigate a repeated global game in which players may observe a subset of previous actions. The experimental results fit the model well when allowing for some error in decision making. Shurchkov (2013) uses a two stage global game to investigate how subjects respond to the arrival of new information. She finds that arrival of new and more precise information after a failed attack increases subjects aggressiveness, while aggression is reduced in the absence of new and more precise information. Duffy and Ochs (2012) find no significant difference between a dynamic and static global-game with respect to the thresholds used by subjects.

Kneeland (2016) analyses global-games where agents have limited depths of reasoning.[10] She theoretically characterizes a coordination game where agents are of different level-k types. Using experimental data from Heinemann, Nagel, and Ockenfels (2004), she shows that the level-k model fits the data better than the rational expectations equilibrium model. Relative to this paper, we provide a novel theoretical prediction of a level-k model, namely on the effect of changes in information dispersion on strategic cutoffs, and show experimental support for this prediction.

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[10]Cornand and Heinemann (2014) analyze the relative weighting of public and private signals in a global game by a k-level model and a cognitive hierarchy model. In explaining deviations from their global games equilibrium Szkup and Trevino (2017) contrast their model of sentiments with several alternative models, one being a level k-model. In their k-level model level zero players are assumed to randomize uniformly over actions. This is in contrast to the distributional assumption used in Kneeland (2016), and in contrast to the estimation approach used in this paper.

3.2   Theoretical predictions

Set-up

We consider a modification of the game studied in Iachan and Nenov (2015). It nests a number of regime change games studied in the literature, such as currency crises, debt rollover crises, bank runs, and political change. There are several differences in our environment relative to that paper. Most importantly, we assume that there is a discrete number N of players. This will allow us to test the predictions of our model in a laboratory experiment.

Agents take a binary action $s_i \in \{0, 1\}$ simultaneously. We interpret $s_i = 1$ as player i attacking the status quo. We let $Z = \sum_i s_i$ denote the number of agents which choose $s_i = 1$. Regime change occurs if at least a fraction $g \in (0, 1)$ of players attack. Therefore, regime change occurs if, and only if, $\frac{Z}{N} \geq g$ or $Z \geq gN$. We define $G_N \equiv \lceil gN \rceil$, so that regime change occurs if, and only if, $Z \geq G_N$. A state variable Y (the fundamentals) determines agent's payoffs, and also the minimal number of agents required for a successful attack. We assume that $Y \sim U(0, M)$, for $M > 0$, is not directly observed by agents , who hold this distribution as their prior belief about the state.

We normalize the payoff from action $s_i = 0$ to zero in the case of both regime change and status quo survival and specify the payoffs in case of $s_i = 1$ as follows: the payoff to a player who attacks is $D(Y)$ in case of regime change and $U(Y)$ in case of status quo survival. We assume that $D(Y) > 0$ and $U(Y) < 0$ and that both are either constant or strictly increasing in Y. As a consequence, actions are strategic complements.

Before choosing actions, agents observe noisy signals about the state Y. Specifically, we assume that player i observes a signal $x_i = Y + \eta_i$, where $\eta_i \sim U[-\epsilon, \epsilon]$ and i.i.d across players, $\epsilon > 0$, and $\epsilon \ll M$. Also, η_i is independent of the realization of Y. We define $E_{x_i}[\cdot]$ as the expectation with respect to the information set of an agent that receives signal x_i.

Equilibrium

The definition of a Bayesian Nash Equilibrium for our game is standard. We restrict attention to equilibria in monotone strategies. A monotone strategy Y^* is such that $s(x_i) = 1$ iff $x_i > Y^*$. In that case it is straightforward to apply standard results from global games to show that there is a unique equilibrium and that the equilibrium is in monotone strategies.

We call the critical value Y^* the *strategic threshold* of agent's actions. Note that for a given value Y^* in the finite-player case, the number of players who observe a signal above Y^* and thus choose $s_i = 1$ is stochastic. Given a value of the fundamental Y, with signals uniformly distributed on the interval $[Y - \epsilon, Y + \epsilon]$, the probability that at least K players get a signal above Y^* is given by the tail distribution of a Binomial random variable

$$\overline{F}_N(K, Y, Y^*) = \sum_{k \geq K}^{N} \binom{N}{k} p(Y, Y^*, \epsilon)^k (1 - p(Y, Y^*, \epsilon))^{N-k} \tag{3.1}$$

where

$$p(Y, Y^*, \epsilon) = \min \left\{ \max \left\{ 0, \frac{Y + \epsilon - Y^*}{2\epsilon} \right\}, 1 \right\} \tag{3.2}$$

Therefore, the probability of regime change given a state Y is

$$P(Y, Y^*) \equiv \overline{F}_N(G_N, Y, Y^*) \tag{3.3}$$

Note that $P(Y, Y^*) = 1$ for $Y \geq Y^* + \epsilon$ and $P(Y, Y^*) = 0$ for $Y \leq Y^* - \epsilon$. Also, since $P(Y, Y^*)$ is defined as a tail distribution evaluated at G_N, it is decreasing in G_N (or equivalently in g), $\forall Y$, so that a higher value of g lowers the probability of regime change for a given value of Y^*. It is also convenient to define the probability of regime change for a player that attacks ($s_i = 1$). We define this probability by $\tilde{P}(Y, Y^*)$. Specifically, a player that attacks expects regime change to occur if at least $G_N - 1$ of the remaining $N - 1$ other players attack, which gives

$$\tilde{P}(Y, Y^*) \equiv \overline{F}_{N-1}(G_N - 1, Y, Y^*) \tag{3.4}$$

Given this probability of regime change, Y^* is determined by an indifference condition for a marginal agent - a player who observes a signal $x_i = Y^*$. Specifically, Y^* solves

$$E_{Y^*} \left[D(Y) \tilde{P}(Y, Y^*) + U(Y) \left(1 - \tilde{P}(Y, Y^*) \right) \right] = 0. \tag{3.5}$$

That is, for a marginal agent, the expected payoff from attacking equals the payoff from not attacking.

As shown by Iachan and Nenov (2015), the effect of information quality on the equilibrium of this game depends on a comparison of the sensitivities of payoffs in the case of regime change and status quo survival. In our experiment, we focus on the case where $U(Y) = U < 0$ and $D(Y)$ is strictly increasing in Y. This nests many global games applications, such as the literature on currency crises (Morris and Shin, 1998).

The prediction of the model that we want to test experimentally is the comparative static of Y^* with respect to increases in ϵ. As shown by Iachan and Nenov (2015), in this context increased information dispersion is destabilizing. That is, if $N \to \infty$, $U(Y) = U < 0$, $\forall Y$ and $D(Y)$ is strictly increasing, then $\frac{\partial Y^*}{\partial \epsilon} < 0$.

3.3   Experimental implementation

In order to implement the model in the lab, we closely follow Heinemann, Nagel, and Ockenfels (2004).[11] The experiment is implemented as a series of 8 independent periods. In each period each subject makes 10 independent binary choices. We organize subjects in groups of $N = 10$

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[11]We adopt the same payoff functions and other parameters as in their (T=20; Z=60) treatments. Our experiment is based on the same zTree files and the same instructions as their experiment. The only differences, aside from the subject pool, is that we consider groups of 10 rather than 15 subjects and that we replace their complete information treatment with our high noise treatment.

Treatments	Low Noise ($\epsilon = 10$)	High Noise ($\epsilon = 20$)
Theoretical threshold	$Y_L^* = 41.8$	$Y_H^* = 38.2$
Expected treatment difference	$Y_L^* - Y_H^*$ =	3.59

Table 3.1: Theoretical predictions.

with subjects indexed i. The rules of the game is made public knowledge through the reading of instructions aloud. Unique subjects are used in all sessions. The language of the experiment is neutral.

At the beginning of each period, 10 different values of Y is drawn, where $Y \sim U(0, 100)$. For any realization of the fundamentals Y, individual signals x_i are then drawn from $U(Y - \epsilon, Y + \epsilon)$. The signal is revealed to subject i but not to the other subjects in the group. The subjects are then asked to make a decision, A or B for each of the 10 decision situations in that period. In the context of the model outlined above, A correspond to $s_i = 0$ and B correspond to $s_i = 1$. If a subject choose A, he/she receive an endowment. The endowments are set so that the subjects can not go bankrupt. If the subject choose B, he/she receives the endowment. In addition, subjects receive a payoff which may depend on both the number of other subjects who chose B and the state Y. The decision B is successful if $a(Y) = [10(80 - Y)/60]$ individuals choose B.

Our payoff structure is as follows. Let Z be the number of agents in a group that attacks. $\pi(Y, Z)$ is the net-payoff from choosing A, given the fundamental Y and the actions of the group members. $\pi(Y, Z)$ is increasing in Y.

$$\pi(Y, Z) = \begin{cases} Y - 20 & : Z \geq a(Y) \\ -20 & : Z < a(Y) \end{cases} \tag{3.6}$$

With this set - up, observe that playing A is dominant if $Y < 20$ and playing B is dominant if $Y > 74$. We run a simple design in which the only treatment is the noise-term ϵ_j in the private signals. Let Y_j^* denote the theory-implied strategic threshold for treatment $j = \{L, H\}$. The theoretical predictions are summarized in Table 3.1.

We obtained data on 8 groups in the High noise treatment and 8 groups in the Low Noise treatment, a total of 160 subjects. The sessions were run in the BI Research Lab from May 2016 to June 2017. The experiment was programmed in z-Tree (Fischbacher (2007)) and subjects were recruited from the general student populations of BI Norwegian Business School and the University of Oslo using the software ORSEE (Greiner (2015)).

3.4   Results

Our first question is to what extent subjects follow the equilibrium requirement of using undomi-
nated threshold strategies in our experiment. For each player i and each period t, let x_{it}^A be the
highest signal at which subject i chose A and x_{it}^B be the lowest signal at which subject i chose B. We
say that a subjects behavior is consistent with a threshold strategy if for each t, $x_{it}^B \geq x_{it}^A$. Letting
ϵ be the noise in each treatment ($\epsilon \in \{10, 20\}$), observe that playing B is dominated by A whenever
an individual signal $x_{it} < 20 - \epsilon$ and A is dominated by B whenever $x_{it} > 74 + \epsilon$. We say that
a subjects behavior is consistent with an undominated threshold strategy if it is consistent with a
threshold strategy, $x_{it}^B \geq 20 - \epsilon$ and $x_{it}^A \leq 74 + \epsilon$.

Overall, the observed behavior by the subjects is largely consistent with playing undominated
threshold strategies. On average, 89 % of the subjects play consistent with undominated threshold
strategies in the Low Noise treatment. In the High Noise treatment, the corresponding number is
92%. There is also some evidence on an increasing reliance on undominated threshold strategies
over time. Figure 3.1 shows the evolution in the use of threshold strategies over time for each of
our treatments. With the exception of a drop towards the end in both treatments, the percentage
of subjects whose behavior is consistent with undominated threshold strategies is increasing as play
progresses.

| Low Noise | High Noise |
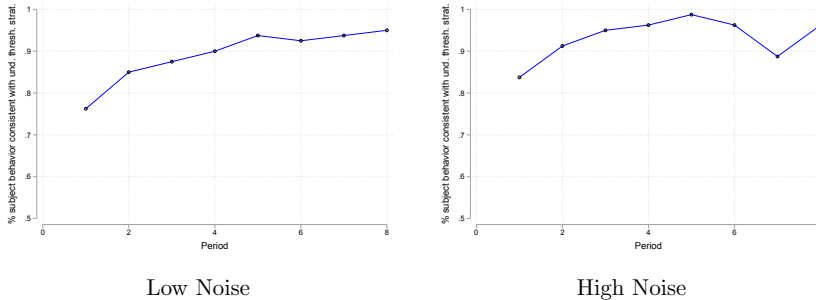
Figure 3.1: Percentage of subjects, whose behavior is consistent with undominated threshold strategies.

Result 1 (Threshold strategies): *Subjects play largely consistent with undominated threshold
strategies.*

To estimate strategic thresholds, we follow Heinemann, Nagel, and Ockenfels (2004) and fit a
cumulative logistic distribution function

$$\Pr\left(B|x\right) = \frac{1}{1 + \exp(\alpha - \beta x)} \tag{3.7}$$

for each group. The mean of the distribution, $\dfrac{\hat{\alpha}}{\hat{\beta}}$ is interpreted as the average strategic threshold
within that group.

In what follows we focus on initial behavior since final outcomes are typically determined by initial choices (see result 4). Table 3.2 reports the strategic thresholds using first period data and average behavior per group as observations. Data in the table are ranked in ascending order for each treatment. As is evident, in each ordered pair of groups the estimated threshold is higher in the High Noise treatment.

Group #	Low noise	High noise
1	26.2	32.6
2	30.3	34.3
3	35.0	36.3
4	38.0	40.3
5	39.3	42.0
6	43.9	47.6
7	44.5	51.5
8	46.4	53.8
Mean threshold (Y_j)	37.9	42.3
Standard deviation	7.1	8.0

Table 3.2: Estimated strategic thresholds; first period data only, ranked groups.

Having estimated the strategic thresholds across groups and treatments, we proceed to testing the model predictions. Additional analysis are provided in Appendix B.2.

A crucial comparative statics of the model is that the estimated threshold in the High Noise treatment should be lower than in the Low Noise treatment. From Table 3.2 the observed difference, averaging over groups in each treatment, is the opposite: the estimated threshold in the High Noise treatment is 4.4 units higher than the estimated threshold in the Low Noise treatment.
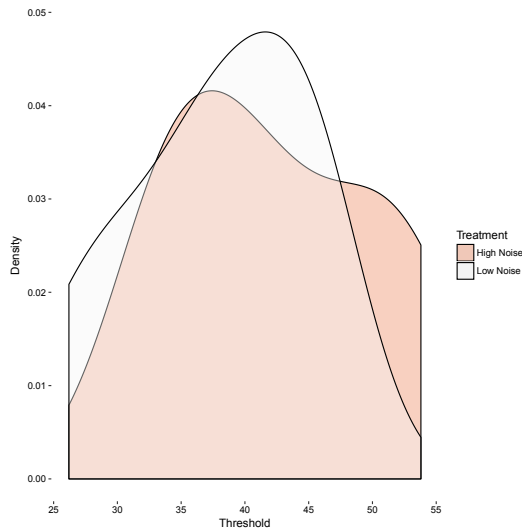
Figure 3.2: Kernel density of strategic thresholds for low- and high-noise treatments.

In Figure 3.2, we plot kernel densities based on the estimated strategic thresholds. As indicated by the figure, there is substantial overlap in the two densities. The kernel density plot and the average point-estimates of strategic thresholds suggests that the comparative statics go opposite of what theory predicts. To formally test whether the difference across treatments is significant, we follow a conservative approach and run a Mann-Whitney U-test where we compare the rank-sums of estimated strategic thresholds using group averages as units of observation. The null hypothesis is that the strategic threshold is not higher in the Low Noise treatment than in the High Noise treatment. The results are shown in Table 3.3. As is clear from the bottom row, we can not reject the null hypothesis that $Y_L^* - Y_H^* \leq 0$ at conventional significance levels.

Treatment	Obs	Rank sum	Expected
Low Noise	8	59	68
High Noise	8	77	68
p-value			0.17

Table 3.3: One sided Mann-Whitney U-test of comparative statics.

Result 2 (Comparative statics): *We can not reject the null hypothesis that the estimated strategic threshold is not higher in the Low Noise treatment.*

According to the model the treatment difference between the estimated thresholds should be approximately 3.6. As noted the observed difference is -4.4. Table 3.4 reports the results from a two

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sided Mann-Whitney U test where the null hypothesis is that the difference in estimated strategic thresholds is 3.6. The test uses only first period data and have group averages as units of observation. We reject the null that $\bar{Y}_L - \bar{Y}_H = 3.6$ with a p-value of 10 % indicating that, if anything, under our parametrization the comparative statics goes opposite of what theory predicts.[12]

Treatment	Obs	Rank sum	Expected
$Y_L^* - \bar{Y}_L$	8	52.5	68
$Y_H^* - \bar{Y}_H$	8	83.5	68
	p-value		0.10

Table 3.4: Two sided Mann-Whitney U-test of treatment difference.

Result 3 (Treatment difference): *The treatment difference is significantly different from what is implied by theory.*

The evolution of the average estimated thresholds over time is shown in Figure 3.3. Interestingly, while the high noise treatment have a higher estimated strategic threshold in the initial period, it has a lower estimated strategic threshold in the final period, more in line with theory. However, the standard deviations across groups within treatments are large and the average estimated thresholds are higher in the High Noise treatment in 6 out of 8 periods. The absence of a clear convergence pattern over time is also observed in Heinemann, Nagel, and Ockenfels (2004).[13]

Result 4 (Evolution of play): *There is no clear convergence of behavior over time.*
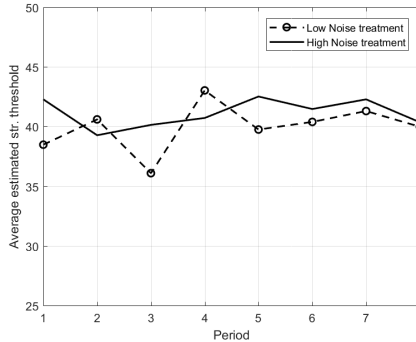
Figure 3.3: Average estimated strategic thresholds for each treatment, by period.

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[12]Note that $\bar{Y}_L - \bar{Y}_H = 3.6 \Rightarrow Y_L^* - \bar{Y}_L = Y_H^* - \bar{Y}_H$. Note also that in a parametric t-test we are able to reject this null at the 5 % level.

[13]Cabarales, Nagel, and Armenter (2007), in contrast, observe convergence towards equilibrium in their simplified global games set-up.

3.5   Deviations from equilibrium theory

The results in the previous section suggests two issues. First, agents strategic cutoffs respond less to information quality than predicted by the theory. Second, average estimated strategic cutoffs suggest that the comparative statics go in the opposite direction relative to the theory. As noted in the literature section this finding is common with several experiments on global games, including Heinemann, Nagel, and Ockenfels (2004) which we replicate closely. In this section, we explore one possible explanation that can jointly explain these two findings.

The theory-implied unique strategic threshold requires an infinite number of rounds of iterated deletion of strictly dominated strategies. There is ample experimental evidence (e.g. Kneeland (2015)) suggesting that most agents employ finite and relatively low number of rounds of iterated deletion of strictly dominated strategies. If agents behave in this way, the set of rationalizable strategies is no longer a singleton and there is also substantial overlap between rationalizable strategies in our two treatments. For example, Figure 3.4 plots the set of k-th round rationalizable strategies for our two treatments and different levels of k, in addition to the observed equilibrium strategies. Note that this is a different concept than k-level thinking that we explore below. Specifically, no assumptions are placed on the behavior of "level-0" agents, other than that they do not play dominated strategies. At commonly observed rounds of elimination (2-4 rounds, according to Kneeland (2015)), both sets of rationalizable strategies contain the observed strategies and also have overlap. Also, consistent with Kneeland (2015), and as shown on the right-hand side of Figure 3.4, the fraction of groups playing rationalizable strategies drops quickly as k increases.
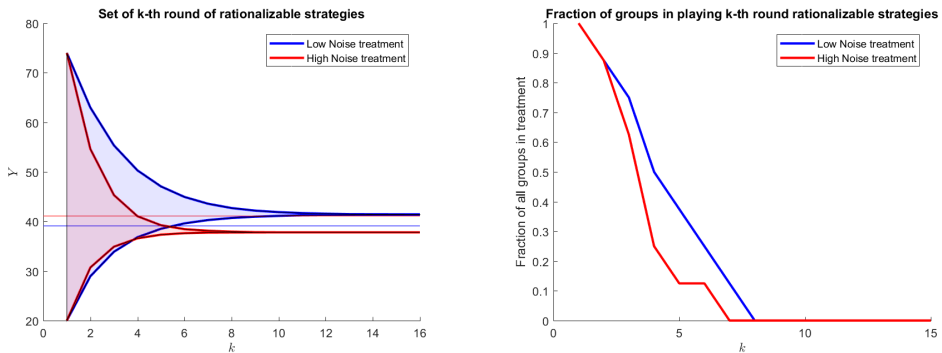
Figure 3.4: Rationalizable strategies at round k (shared area) and estimated average equilibrium strategies (solid horizontal line) (left panel) and fraction of groups playing a round k rationalizable strategy.

These observations suggest that a model of behavior in which agents may engage in a limited number of elimination rounds may help with explaining our experimental findings. One possible model which we explore below is level-k thinking.

3.5.1   Level-k thinking

Level-k thinking is a prominent class of models, featuring limited depths of reasoning and adding a particular structure to agent's beliefs. (Nagel, 1995; Stahl and Wilson, 1995; Kubler and Weizsacker, 2004; Crawford, Costa-Gomes, and Iriberri, 2013). In this framework, each player's behavior is determined by her own cognitive type. Cognitive types are drawn from a discrete distribution over $\{L0, L1, \ldots, LK\}$, where Lk denotes a type that engages in k rounds of reasoning. Specifically, $L0$ types behavior is specified as a model primitive, an $L1$-type assumes that all other agents are $L0$ types, an $L2$ type assumes that all other agents are $L1$ types, etc.

The main appeal of a level-k model in our setting is that it can potentially change the comparative statics from the standard global games theory on how information dispersion affects regime stability. To show this, consider a regime-change global game with a continuum of agents and normally distributed private signals with precision α (variance $\sigma^2 = 1/\alpha$) and diffuse priors. The change in distributional assumptions compared to our experiment follows Kneeland (2016) and is motivated by increased transparency of theoretical results. Derived comparative statics are not sensitive to this change. An agent that chooses $a_i = 0$ obtains a payoff of $x > 0$ regardless of whether there is regime change or not. An agent that chooses $a_i = 1$ obtains a payoff of $D(\theta) > 0$ in case of regime change and 0 otherwise. We assume that $D(.)$ is decreasing in θ. This shift follows Kneeland (2016) and the relatively more standard interpretation of the fundamentals that is used in the theoretical literature. Regime change occurs if at least $g(\theta)$ agents choose $a_i = 1$, where $g(\theta)$ is increasing in θ.

Assume that agents have limited depth of reasoning. Specifically, assume that L0 types play threshold strategies with a cutoff given by θ_{L0}^*, which is prespecified. If all players are L0 types, then regime change occurs for values of the fundamental $\theta < \theta_{L0}^f$, where θ_{L0}^f satisfies

$$g\left(\theta_{L0}^f\right) = \Phi\left(\frac{\theta_{L0}^* - \theta_{L0}^f}{\sigma}\right).$$

Notice that

$$\frac{\partial \theta_{L0}^f}{\partial \sigma} \propto \theta_{L0}^f - \theta_{L0}^*,$$

which is greater or less than 0 depending on how θ_{L0}^f compares to θ_{L0}^*. However, this comparative static also determines how the behavior of types with higher levels of reasoning is affected by changes in signal variance. For example, suppose for illustrative purposes that all agents are L1 types. Given the behavioral assumption underlying level-k thinking, each of these L1 types believes that he is playing against L0 opponents and, so, expects regime change to happen if $\theta < \theta_{L0}^f$. The following Proposition shows that the comparative statics of the strategic cutoff of L1 agents with respect to information dispersion is ambiguous.

Proposition 3.1. *Consider the game outlined above. In this game, the comparative statics of the strategic cutoff of L1 agents with respect to information dispersion is ambiguous.*

Proof. See Appendix B.1.   □

To build some intuition for the result note that the sign of $\frac{\partial \theta^*_{L1}}{\partial \sigma}$ depends on a comparison of θ^f_{L0}, θ^*_{L0}, and θ^*_{L1}. For example, suppose that $\theta^*_{L0} < \theta^f_{L0} < \theta^*_{L1}$. In that case $\frac{\partial \theta^*_{L1}}{\partial \sigma} > 0$. However, suppose that $\theta^f_{L0} < \theta^*_{L0}$ and $\theta^f_{L0} < \theta^*_{L1}$, then it may be the case that $\frac{\partial \theta^*_{L1}}{\partial \sigma} < 0$. Intuitively, as $\sigma \uparrow$, the "payoff sensitivities" effect pushes towards agents becoming more aggressive. However, if $\frac{\partial \theta^f_{L0}}{\partial \sigma} < 0$, then L0 agents anticipate that the regime would survive more often, which makes them less aggressive.

3.5.2   Empirical evaluation

To separate the subjects into different k-level types, we follow Kneeland (2016) and estimate a finite mixture model on data from each of our treatments separately.[14] We allow agents to be L1-types, L2-types and equilibrium types.[15] We assume that each player follows the predictions of a particular type with some error. Specifically, in each decision a subject has a probability of $1 - \epsilon$ of making a decision consistent with her type and a probability of ϵ of making an error. If the player makes an error, the choice is a function of an error density $d^k\left(a^i_q, \lambda\right)$ specified below.

Let q denote a decision round and a^i_q be the choice of individual i in round q. For each subject×type, we can then define the set Q^{ik}, which consists of all rounds where subject i made a decision consistent with type k. Weighting over the different types and summing over all subjects, we get that the log-likelihood of observing a particular sample is

$$\mathcal{L} = \sum_{i=1}^{S} \log \left[\sum_{k=1}^{3} p_k \left(\Pi_{q \in Q^{ik}} \left(1 - \epsilon + \epsilon d^k \left(a^i_q, \lambda\right) \right) \right) \left(\Pi_{q \notin Q^{ik}} \epsilon d^k \left(a^i_q, \lambda\right) \right) \right] \qquad (3.8)$$

The parameter λ is a precision parameter in the error density:

$$d^k \left(a^i_q, \lambda\right) = \frac{\exp\left\{ \lambda S^k_q \left(a^i_q\right) \right\}}{\exp\left\{ \lambda S^k_q \left(\text{attack}\right) \right\} + \exp\left\{ \lambda S^k_q \left(\text{not attack}\right) \right\}}$$

where $S^k_q \left(a^i_q\right)$ denotes the expected payoff of an agent of type k at decision round q who takes action a^i_q.

We fit 5 independent parameters, namely p_1 (the fraction of level-1 agents), p_2 (the fraction of level-2 agents), θ_0 (the strategic threshold of level-0 agents), λ, and ϵ.

The estimated parameters for the first period of play are shown in Table 3.5. The unit of analysis is now individual decisions. The estimated cutoffs of L0-types indicate that such agents are perceived to be playing the payoff dominant action (always attack) with very high probability whenever it is not strictly dominated. This is well in line with the existing literature on coordination experiments (Costa-Gomes, Crawford, and Iriberri, 2009; Crawford, Gneezy, and Rottenstreich, 2008). The estimated fraction of L1 types in the Low Noise (High Noise) treatment is 46 (37) percent, while the estimated fraction of L2 types in the Low Noise (High Noise) treatment is 25 (18) percent. Thus, between 71 and 55 percent of our subjects are estimated to be level-k types. This is somewhat lower

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[14]Details on the estimation procedure is provided in Mofatt (2016), chapter 8.

[15]As in Kneeland (2016), equilibrium types here engage in infinite rounds of reasoning, so they play according to the equilibrium strategies from the global games model.

Parameter	Low Noise	High Noise
Level - 0 cutoff (θ_0)	21.85	28.27
	[3.29]	[5.35]
Fraction of level-1 agents (p_1)	0.46	0.37
	[0.15]	[0.26]
Fraction of level-2 agents (p_2)	0.25	0.18
	[0.13]	[0.11]
Trembling rate (ϵ)	0.58	0.48
	[0.059]	[0.10]
Precision of error density (λ)	0.04	0.04
	[0.01]	[0.03]
n	800	800

Table 3.5: Results from estimating equation (3.8) on data from period 1. Bootstrapped standard errors in brackets.

than comparable papers (Kneeland, 2016). However, it is worth highlighting that the definition of L0 types in our experiment differs relative to Kneeland (2016). While the L0-type defined in Kneeland (2016) attacks with a fixed probability, our L0-type is assumed to be slightly more sophisticated in the sense that he/she responds to the signal obtained.

On average, the probability of making the wrong action relative to the type assigned (the trembling rate) is 58 percent in the Low Noise treatment and 48 percent in the High Noise treatment. The type classification is based on 80 subjects who each make 10 choices. In the Low Noise treatment there are 43 observations that separate the predictions of L1 and L2 types, 93 observations that separate the predictions of L1 and equilibrium types, and 50 observations that separate the predictions of L2 and equilibrium types. In the High Noise treatment there are 19 observations that separate the rpedictions L1 and L2 types, 49 observations that separate the predictions of L1 and equilibrium types and 30 observations that separate the predictions of L2 and equilibrium types.

We now proceed with an evaluation of whether our estimates can rationalize the observation that subjects on average are more aggressive in the High Noise treatment. Consider Figure 3.5. The left panel concerns our Low Noise treatment while the right panel concerns our High Noise treatment. Red curves provide reaction functions for L1 players while black curves provide reaction functions for L2 players. The estimated thresholds for (perceived) L0 players are taken from Table 3.5 and are marked in the figure by the vertical red dotted lines. The thresholds of L1 players are marked by the vertical black dotted lines.

Consider first the Low Noise treatment. The estimated threshold of an L0 player is 21.9. The threshold of an L1 player is then 30.0. It is found at the intersection of the red dotted line and the reaction function of the L1 player. The threshold of an L2 player is 37.1. It is found at the intersection of the black dotted line and the reaction function of the L2 player. Consider next the High Noise treatment. The estimated threshold of an L0 player is 28.3. The thresholds of higher order types then follows and is 33.8 for L1 types and 38.2 for L2 types. Weighting the thresholds of cognitive types by their estimated frequencies provides an average estimated threshold

per treatment.[16]   The average estimated threshold turns out to be 1.5 units higher in the High Noise than in the Low Noise treatment. While the sign is identical, the estimated difference from the level-k model is somewhat lower than the estimated difference in Table 3.2, which was based on group averages and disregarded cognitive types.

Result 5 (Observed threshold difference): *More aggressive play in the High Noise than the Low Noise treatment is rationalized by the estimated level k model.*
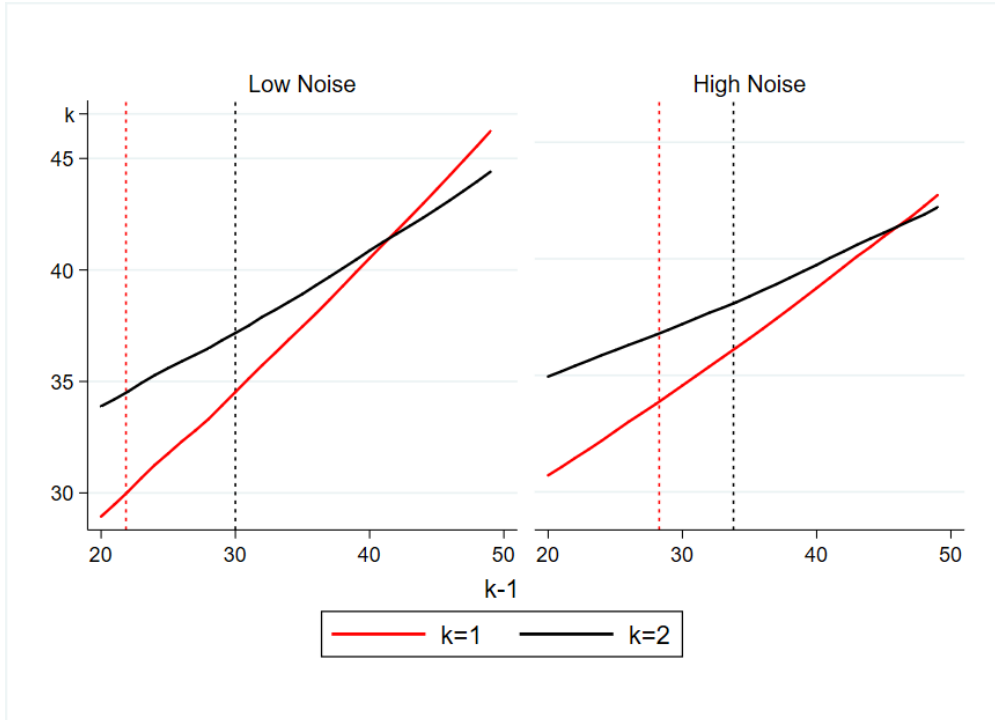
Figure 3.5: Reaction functions of L1 types (red curves) and L2 types (black curves). Thresholds of L0 types (red dotted lines) and L1 types (black dotted lines)

3.6   Concluding comments

In this paper we experimentally test how changes in information dispersion affects regime stability in a standard global games model. We show that regime stability is relatively insensitive to changes in information dispersion. Furthermore, we obtain experimental evidence that agents become less aggressive when information dispersion increases. This is at odds with standard Global Games

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[16]The equilibrium type tresholds are found in Table (3.1) while the estimated frequencies of equilibrium players $(1 - p_1 - p_2)$ are taken from Table 3.5.

theory, but in line with previous experimental findings. We show that bringing a behavioral model in which agents have level-k thinking into the global games model can help explain our experimental finding both theoretically and empirically.

Chapter 4

Are negative nominal interest rates expansionary?

with Gauti B. Eggertsson and Ella Getz Wold

4.1 Introduction

Nominal interest rates have been declining over the past decades, resulting in record low policy rates. Several countries have interest rates close to or at zero percent, and some have gone even further. Between 2012 and 2016, a handful of central banks reduced their key policy rates below zero for the first time in history. While *real* interest rates have been negative on several occasions, the use of negative *nominal* rates prompted a new discussion on the relevance of the zero lower bound. The recent experience with negative interest rates in Japan and a number of European countries makes it clear that negative nominal interest rates should be viewed as part of the central bankers toolbox. However, the question of how negative interest rates affect the macroeconomy is largely unresolved. Our goal in this paper is to answer this question.

Understanding how negative nominal interest rates affect the economy is important in preparing for the next economic downturn. Interest rates have been declining for more than three decades, resulting in worries about secular stagnation (see e.g. Summers 2014, Eggertsson and Mehrotra 2014 and Caballero and Farhi 2017). In a recent working paper, Kiley and Roberts (2017) estimate that the zero lower bound on nominal interest rates will bind 30-40 percent of the time going forward. Whether setting a negative interest rate is expansionary is therefore of first order importance.

Why did central banks try this untested policy? In short, they argued that there is nothing special about policy rates falling below zero. When announcing a negative policy rate, the Swedish Riksbank wrote in their monetary policy report that "*Cutting the repo rate below zero, at least if the cuts are in total not very large, is expected to have similar effects to repo-rate cuts when the repo rate is positive, as all channels in the transmission mechanism can be expected to be active*" (Riksbanken, 2015). Similarly, the Swiss National Bank declared that *"the laws of economics do not change significantly when interest rates turn negative"* (Jordan, 2016). Many are skeptical however.

For instance, Mark Carney of the Bank of England is "... *not a fan of negative interest rates*" and argues that *"we see the negative consequences of them through the financial system"* (Carney, 2016). One such consequence might be the adverse impact on bank profitability, which has caused concern in the Euro Area in particular (Financial Times, 2016). Consistent with this view, Waller (2016) coins the policy a "tax in sheep's clothing", arguing that negative interest rates act as any other tax on the banking system and thus reduces credit growth.[1]

In this paper we investigate the impact of negative central bank rates on the macroeconomy, both from an empirical and theoretical perspective.[2] The first main contribution of the paper is to use a combination of aggregate and bank level data to examine the pass-through of negative nominal central bank rates via the banking system. Using aggregate data, across six different economies, we show how negative policy rates have had limited pass-through to bank deposit rates, i.e. the rates customers face when they deposit their money in banks, and to lending rates, i.e. the rate at which customers borrow from banks. Making inferences about whether negative interest rates are expansionary based on aggregate data is challenging, however. We therefore proceed by using a unique and novel, daily bank level dataset on lending rates from Sweden, to explore the decoupling of lending rates from the policy rate. Due to the high frequency nature of the data, we are able to estimate the causal effect of policy rate cuts on bank lending rates. We can then compare the transmission mechanism of monetary policy in positive and negative territory. We document a striking decline in pass-through and a substantial increase in heterogeneity across banks for a wide range of mortgage loans once the policy rate becomes negative. We show that this increase in heterogeneity is linked to variation in the reliance on deposit financing: the higher the dependence on deposit financing, the smaller the effect on lending rates. Finally, using a difference-in-differences approach, we show that banks with high deposit shares have significantly lower credit growth once the policy rate becomes negative, consistent with similar findings for the Euro Area (Heider, Saidi, and Schepens, 2016).

Motivated by these empirical results, the second main contribution of the paper is methodological. We construct a model, building on several papers from the existing literature, which allows us to address in the most simple setting how changes to the central bank policy rate filters though the banking system to various other interest rates, and ultimately determines aggregate output. At a minimum, such a model needs to recognize the role of money as a store of value, give a role to banks in order to allow for separate lending and borrowing rates, as well as having a well defined policy rate that may differ from the rates depositors and borrowers face. We construct a simple New Keynesian DSGE model which nests the standard one-period interest rate textbook New Keynesian model (see e.g. Woodford, 2003b) and other recent variations. Our framework has four main elements. First, we explicitly introduce money along with storage costs to clarify the role of money as a store of value and illustrate how this may generate a bound on deposit rates. Second, we in-

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[1]Other skeptics include Stiglitz (2016) and McAndrews (2015).

[2]Note that we do not attempt to evaluate the impact of other monetary policy measures which occurred simultaneously with negative interest rates. That is, we focus exclusively on the effect of negative interest rates, and do not attempt to address the effectiveness of asset purchase programs or programs intended to provide banks with cheap financing (such as the TLTRO program initiated by the ECB).

corporate a banking sector and nominal frictions along the lines of Benigno, Eggertsson, and Romei (2014), which delivers well defined deposit and lending rates. Third, we incorporate demand for central bank reserves as in Curdia and Woodford (2011) in order to obtain a policy rate which can potentially differ from the commercial bank deposit rate. Fourth, we allow for the possibility that the cost of bank intermediation depends on bank's net worth as in Gertler and Kiyotaki (2010). The central bank sets the interest rate on reserves, and can choose to implement a negative policy rate as banks are willing to pay for the transaction services provided by reserves. However, due to the possibility of using money to store value, the deposit rate faced by commercial bank depositors is bounded at some level (possibly negative), in line with our empirical findings. The reason is simple: the bank's customers will choose to store their wealth in terms of paper currency if charged too much by the bank. We stipulate explicit conditions on the storage cost of money that guarantees a well-defined lower bound.[3]

Away from the lower bound on the deposit rate, the central bank can stimulate the economy by lowering the policy rate. This reduces both the deposit rate and the rate at which households can borrow, thereby increasing demand. We show however, that once the deposit rate reaches its effective lower bound, reducing the policy rate further is no longer expansionary. As the central bank looses its ability to control the deposit rate, it cannot stimulate the demand of savers via the traditional intertemporal substitution channel. Furthermore, as bank's funding costs (via deposits) are no longer responsive to the policy rate, the bank lending channel of monetary policy breaks down. There is no stimulative effect via lower borrowing rates. Hence, as long as the deposit rate is bounded, a negative central bank rate fails to bring the economy out of a recession. We further show that if bank profits affect bank's intermediation costs, due to for instance informational asymmetries between the bank and its creditors as in Gertler and Kiyotaki (2010), negative interest rates can be contractionary through a reduction in bank's net worth.

Literature Review   Jackson (2015) and Bech and Malkhozov (2016) document the limited pass-through of negative policy rates to aggregate bank rates, but do not evaluate the effects on the macroeconomy. Heider, Saidi, and Schepens (2016) and Basten and Mariathasan (2018) document that negative policy rates has not lead to negative deposit rates in the Euro Area and Switzerland, respectively. While Basten and Mariathasan (2018) find that Swiss banks primarily reduce reserves in response to negative rates, Heider, Saidi, and Schepens (2016) find that banks with higher deposit shares have lower lending growth in the post-zero environment. While Heider, Saidi, and Schepens (2016) argue that this is a result of the lower bound on deposit rates, no attempt is made to formalize the mechanisms at play. We contribute to the empirical literature on the pass-through

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[3]There are other reasons why there might be a lower bound on the deposit rate, which we do not explore in this paper. Rather, we choose to introduce a lower bound as a consequence of the combination of money as a store of value and storage costs, motivated by both the existing literature and empirical evidence suggesting that households would withdraw their cash had they faced a negative interest rate, see Figure 4.2 in Appendix C.1. The existence of a zero lower bound due to potential cash withdrawals is also consistent with the observation we make that the bound appears strongest for household depositors. The reason *why* there exists a lower bound is an interesting and important question, however it is not important for our results.

of negative rates by i) providing a comprehensive analysis of the pass-through of negative policy rates to aggregate lending and deposit rates across all relevant countries, and more importantly ii) exploit a unique dataset on lending rates to provide novel micro level evidence on the decoupling of lending rates from the policy rate. Furthermore, we show how the lack of pass-through to lending rates can be explained by cross-sectional variation in the reliance on deposit financing.

Given the radical nature of the policy experiment pursued by several central banks, the theoretical literature is perhaps surprisingly silent on the expected effect of this policy.[45] Two important exceptions are Brunnermeier and Koby (2016) and Rognlie (2015). Following the introduction of negative rates, there were concerns that bank profits would be harmed and the policy as such could be contractionary. Brunnermeier and Koby (2016) models related concerns, by defining the reversal rate as the interest rate at which further policy rate reductions *increase* commercial bank lending rates due to the negative effect of reduced net interest margins. This reversal rate, however, can in principle be either positive or negative, so it is unrelated to the observed lower bound on deposit rates, which is central to both the empirical and theoretical analysis of our paper. Furthermore, Brunnermeier and Koby (2016) do not analyze the general equilibrium impact of interest rate reductions on output and inflation. Rognlie (2015) allows for a negative interest rate due to money storage costs. However, in his model households face only one interest rate, and the central bank can control this interest rate directly. Thus, the model does not allow for a separate bound on deposit rates. Hence, neither of these papers capture the key mechanism in our paper, which is driven by an empirical observation which was by no means obvious ex ante: as the lower bound on the commercial bank deposit rate becomes binding, the connection between the central bank's policy rate (which can be negative) and the rest of the interest rates in the economy breaks down. Our main theoretical contribution is therefore building a model that can deliver this mechanism and then, in the context of our model, analyzing the effect of negative policy rates on aggregate output and inflation.

There also exists an older literature, dating at least back to the work of Silvio Gesell more than a hundred years ago, which contemplates more radical monetary policy regime changes than we do here (Gesell, 1916). This literature has been rapidly growing in recent years. In our model, the storage cost of money, and hence the lower bound, is treated as fixed. However, policy reforms could potentially alter the lower bound or even remove it completely. An example of such policies is a direct tax on paper currency, as proposed first by Gesell and discussed in detail by Goodfriend (2000) and Buiter and Panigirtzoglou (2003). Another possibility is abolishing paper currency altogether. This policy is discussed in, among others, Agarwal and Kimball (2015) and Rogoff (2017a), who also suggest more elaborate policy regimes to circumvent the ZLB. The results presented here should not be considered as rebuffing any of these ideas. Rather, we are simply pointing out that under the current institutional framework, empirical evidence and a stylized variation of the standard New

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[4]There is however a large literature on the effects of the zero lower bound. See for example Krugman (1998) and Eggertsson and Woodford (2006) for two early contributions.

[5]Our paper is also related to an empirical literature on the connection between interest rate levels and bank profits (Borio and Gambacorta 2017, Kerbl and Sigmund 2017), as well as a theoretical literature linking credit supply to banks net worth (Holmstrom and Tirole 1997, Gertler and Kiyotaki 2010).

Keynesian model do not seem to support the idea that a negative interest rate policy is an effective tool to stimulate aggregate demand. This should, in fact, be read as a motivation to study further more radical proposals such as those presented by Gesell over a century ago and more recently in the work of authors such as Goodfriend (2000), Buiter and Panigirtzoglou (2003) and Agarwal and Kimball (2015).

4.2   Negative Interest Rates In Practice

4.2.1   Aggregate evidence

In this section, we use aggregate data retrieved from central banks and statistical agencies for each of the six economies we discuss, to shed light on the evolution of aggregate deposit and lending rates following the introduction of negative policy rates.

Deposit rates   In Figure 4.1 we plot deposit rates for six economic areas in which the policy rate is negative. Starting in the upper left corner, the Swedish central bank lowered its key policy rate below zero in February 2015. Deposit rates, which in Sweden are usually below the policy rate, did not follow the central bank rate into negative territory. Instead, deposit rates for both households and firms remain stuck at, or just above, zero. A similar picture emerges for Denmark, as illustrated in the upper right corner. The Danish central bank crossed the zero lower bound twice, first in July 2012 and then in September 2014. As was the case for Sweden, the negative policy rate has not been transmitted to household deposit rates. For corporations however, the average deposit rate is slightly below zero.

Consider next the Swiss and Japanese case in the middle row of Figure 4.1. Switzerland implemented a negative policy rate in December 2014, while the central bank in Japan lowered its key policy rate below zero in early 2016. The deposit rates in both countries were already very low, and did not follow the policy rate into negative territory. As a result, the impact on deposit rates was limited.

Figure 4.1: Aggregate deposit rates for Sweden, Denmark, Switzerland, Japan, the Euro Area and Germany. The policy rates are defined as the Repo Rate (Sweden), the Certificates of Deposit Rate (Denmark), SARON (Switzerland), the Uncollaterized Overnight Call Rate (Japan) and the Deposit Rate (Euro Area and Germany). The red vertical lines mark the month in which policy rates became negative. Source: The Riksbank, Statistics Sweden, the Danish National Bank (DNB), the Swiss National Bank (SNB), Bank of Japan, and the European Central Bank (ECB).

Finally, interest rates for the Euro Area are depicted in the bottom row of Figure 4.1. The ECB reduced its key policy rate below zero in June 2014. As seen from the left panel, aggregate deposit rates are high in the Euro Area and therefore have more room to fall before reaching the zero lower bound. Looking at Germany only, in the bottom right of the figure, we see that deposit rates are somewhat lower. Although the corporate deposit rate in Germany appears to have dipped slightly below zero on some occasions, the Euro Area interest rate data again supports the notion that deposit rates appear bounded at some level close to zero.

Note that because banks have generally been reluctant to pass negative interest rates on to their clients, especially to households, we do not know to what extent negative deposit rates would lead to an outflow of deposits. However, in a recent survey by the ING, 76 % of the respondents said they would withdraw their money if the interest rate on their saving account turned negative (ING, 2015), see Figure 4.2.
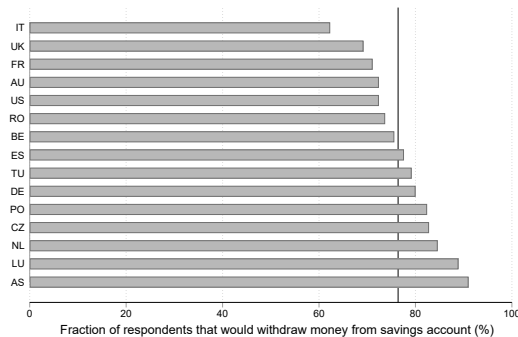
Figure 4.2: Fraction of households who would withdraw money from their savings account if they were levied a negative interest rate. Solid line represent unweighted average of 76.4 %. Source: ING (2015)

Lending rates Although most deposit rates appear bounded by zero, one might still expect negative policy rates to lower *lending* rates. As lending rates are usually above the central bank policy rate, they are all well above zero. Here we show that the pass-through of the policy rate to lending rates appears weakened when the policy rate becomes negative, an empirical finding our model will replicate. In Figure 4.3 we plot bank lending rates for the six economic areas considered above. While lending rates usually follow the policy rate closely, there appears to be a disconnect once the policy rate breaks the zero lower bound, a feature which will become starker once we consider disaggregated bank data. Looking at the aggregate data in Figure 4.3, lending rates in Sweden, Denmark and Switzerland seem less sensitive to the respective policy rates once they become negative. There appears to be some reduction in Japanese lending rates at the time the policy rate went negative, but because there are no further interest rate reductions in negative territory the Japanese case is less informative.[6] Again, the Euro Area is somewhat of an outlier, as lending rates have decreased.[7] This is not surprising however, in light of the higher-than-zero deposit rates we documented in the previous fact. Again, for the case of Germany, in which the zero lower bound on the deposit rate *is* binding for household deposits, lending rates appear less responsive. For the countries in which the deposit rate seems to have reached its lower bound, the limited reduction in lending rates means that the net interest rate margin is largely unaffected.

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[6]The initial reduction in Japanese lending rates could be caused by the positive part of the policy rate cut, i.e. going from a positive policy rate to a zero policy rate.

[7]When considering the Euro Area it is worth noting that the negative interest rate policy was implemented together with a host of other credit easing measures, some of which implied direct lending from the ECB to commercial banks at a (potentially) negative interest rate. That policy is better characterized as a credit subsidy rather than charging interest on reserves, which the commercial banks hold in positive amounts at the central bank.
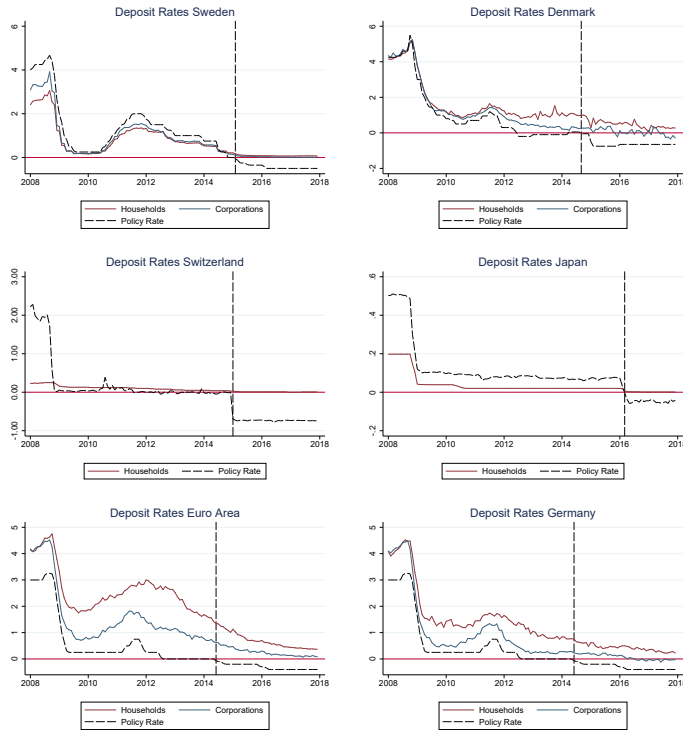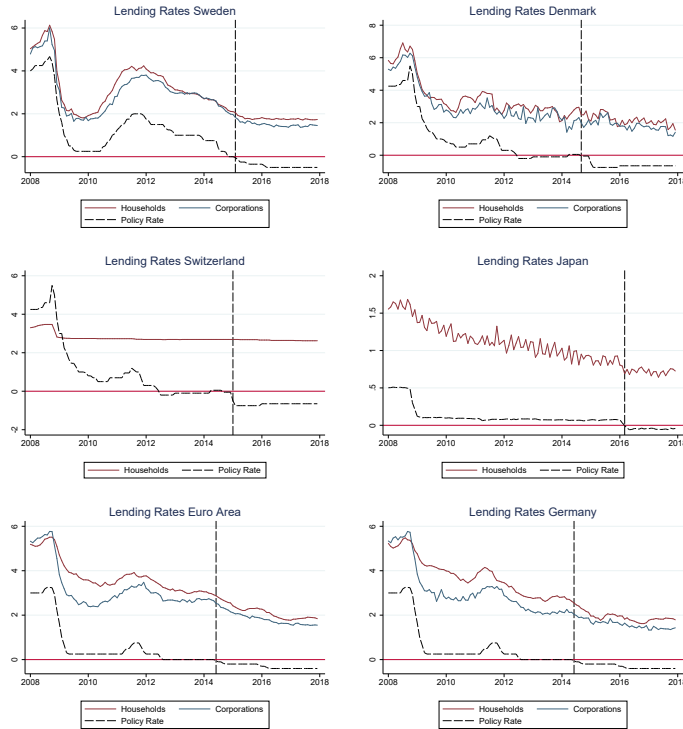
Figure 4.3: Aggregate lending rates for Sweden, Denmark, Switzerland, Japan, the Euro Area and Germany. The policy rates are defined as the Repo Rate (Sweden), the Certificates of Deposit Rate (Denmark), SARON (Switzerland), the Uncollaterized Overnight Call Rate (Japan) and the Deposit Rate (Euro Area and Germany). The red vertical lines mark the month in which policy rates became negative. Source: The Riksbank, Statistics Sweden, the DNB, the SNB, Bank of Japan, and the ECB.

4.2.2   Bank-level evidence on the pass-through of negative interest rates

To better understand the pass-through of negative policy rates to bank-level rates, we proceed by using two bank level datasets for Swedish banks. First, we use daily bank level data on a rich set of mortgages for the largest Swedish banks, which was provided by the price comparison site *compricer.se*.[8] We exploit the high frequency of the data to evaluate the causal effect of reductions in the policy rate, and compare the monetary policy transmission to lending rates across positive and negative territory. Second, we complement our analysis by using bank level data on monthly lending volumes from Statistics Sweden.

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[8]We have mortgage rates for different periods of fixed interest rates, ranging from one to five years, in addition to floating rates. The fixed interest rate periods for which all financial institutions provide interest rates are 1 year, 2 years, 3 years and 5 years.

Limited pass-through to lending rates   In Figure 4.4 we plot daily bank level mortgage rates for the largest Swedish banks. We show in Figure C.3 in Appendix C.1 that the bank level data can be aggregated up to match the official aggregate mortgage rate data. The vertical lines in Figure 4.4 capture days on which the key policy rate (the repo rate) was lowered. The level of the repo rate is reported on the x-axis. The first two lines capture repo rate reductions in positive territory. On both of these occasions, there is an immediate and homogeneous decline in bank lending rates. The next line marks the day the repo rate turned negative for the first time, and the three proceeding lines capture repo rate reductions in negative territory. The response in bank lending rates to these interest rate cuts are strikingly different. While there is some initial reduction in lending rates, most of the rates increase again shortly thereafter. As a result, the total impact on lending rates is limited.
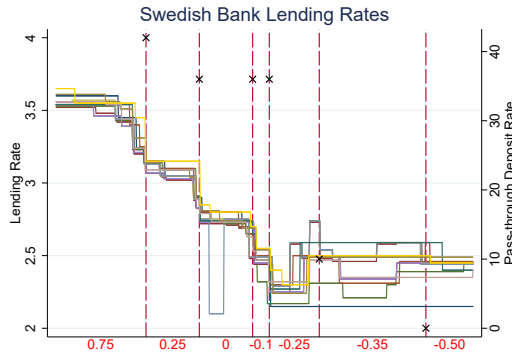
Figure 4.4: Bank-level lending rates in Sweden. Interest rate on mortgages with five-year fixed interest period. The red vertical lines mark days in which the repo rate was lowered. The label on the x-axis shows the value of the repo rate. Small x's denote the change in the deposit rate relative to the change in the policy rate (%), measured on the right y-axis.

We also include in the graph the correlation between the repo rate and the aggregate deposit rate, as illustrated by the black x's measured on the right y-axis. For the first four repo rate reductions in our sample, the change in the aggregate deposit rate was roughly 40 percent of the change in the repo rate. For the last two repo rate cuts however, the change in the aggregate deposit rate was much smaller. This highlights a subtle, but important, point: the pass-through to lending rates is smaller once the deposit rate is no longer responding to further policy rate cuts. This may be exactly when the policy rate goes negative, or as in the Swedish case, shortly thereafter. For the two last repo rate cuts in our sample, there is virtually no pass-through to either the aggregate deposit rate or to bank level mortgage rates.

In Figure 4.5 we depict box plots of bank level correlations between the lending rates and the policy rate. The black box to the left corresponds to the empirical distribution of correlations prior to the Riksbank going negative. The gray box in the middle corresponds to the empirical

distribution for the full period of negative rates. Finally, the blue box to the right corresponds to the empirical distribution of correlations after the deposit rate becomes unresponsive to changes in the repo rate (i.e. the last two policy rate cuts). Consistent with the previous figure, there is a substantial drop in the correlation between bank lending rates and the repo rate once the repo rate becomes negative. This is especially clear for the last two repo cuts, in which deposit rates were essentially bounded. In this case, the average correlation between bank lending rates and the repo rate actually falls slightly below zero.
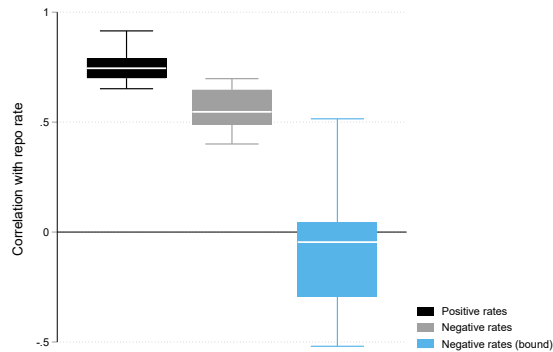
Figure 4.5: The distribution of bank-level correlations between changes in lending rates and the repo-rate when the repo rate is positive ("positive rates"), the repo rate is negative ("negative rates") and the repo rate is negative and the deposit rate is non-responsive ("Negative rates (bound)"). 5-year fixed interest rate period.

The stark reduction in pass-through holds across a wide range of loan types. In Figure 4.6 we plot bank-level lending rates across three different contracts, a floating rate mortgage (3m), a mortgage with a 1 year fixed-rate period (1y) and a mortgage with a 3 year fixed-rate period (3y). In all three cases, we see that the interest rate cuts in negative territory have very limited pass-through to bank lending rates.
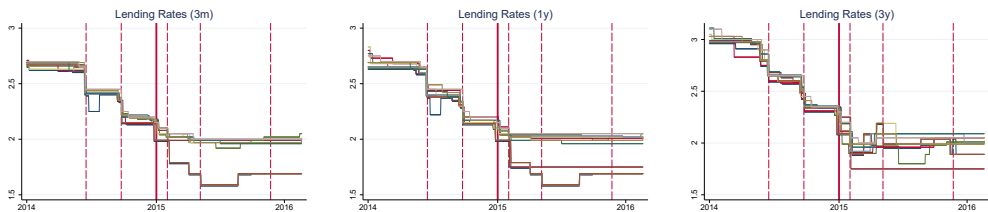
Figure 4.6: Bank level lending rates with a floating interest rate (3m) (left panel) and a fixed interest rate period of 1y (mid panel) and a fixed interest rate period of 3y (right panel). The red solid line capture days with repo rate reductions.

In Table 4.1 we formally test the pass-through of changes in the the repo rate to changes in bank lending rates. We make two comparisons, one where we compare the correlation pre- and post negative rates and one where we compare the correlation prior to negative rates with the correlation for the last two repo cuts, where the pass-through to the aggregate deposit rate was below 10 percent. As seen in the table, the correlation is significantly lower after the introduction of negative interest rates (Panel A) and after the deposit rate reaches its lower bound (Panel B). The reduction is pass-through is statistically significant across all fixed interest-rate periods. Moreover, the drop in correlation is especially large when comparing the pass-through prior to negative rates with the pass-through during the two final policy rate cuts.

Fixed interest rate period:	Floating rate	1y	3y	5y
Mean correlation, before	0.92	0.91	0.82	0.76
Mean correlation, after	0.57	0.58	0.63	0.53
Mean correlation, after bound	0.37	0.27	0.15	-0.01
Panel A. Difference: After - before	-0.35^{***}	-0.33^{***}	-0.19^{***}	-0.22^{***}
p-value	0.00	0.00	0.00	0.00
Panel B. Difference: After bound - before	-0.54^{**}	-0.63^{***}	-0.67^{***}	-0.77^{***}
p-value	0.05	0.00	0.00	0.00

Table 4.1: Correlation between changes in the repo rate and banks lending rates at different maturities. Data collapsed to monthly mean. "After" refer to the time period after the repo rate was first reduced below zero. "After (bound)" refer to the two most recent repo rate cut, where the deposit rate is essentially bounded at zero.

Increased dispersion in bank lending rates   Negative policy rates also leads to a substantial increase in the dispersion of lending rates across banks. In the left panel of Figure 4.7, we plot the minimum and maximum bank lending rate along side the repo rate (the dashed black line). The increase in dispersion after the repo rate turned negative is clearly visible. We also note that the minimum bank lending rate has stayed constant since the first quarter of 2015, despite three policy rate reductions in negative territory. In the right panel of Figure 4.7, we illustrate the increase in dispersion explicitly by plotting the standard deviation of lending rates over time. We first note that the dispersion in bank rates appears to spike around the time when changes to the repo rate are announced. Second, and more importantly for our purpose, there is a sustained increase in dispersion after the zero lower bound is breached.
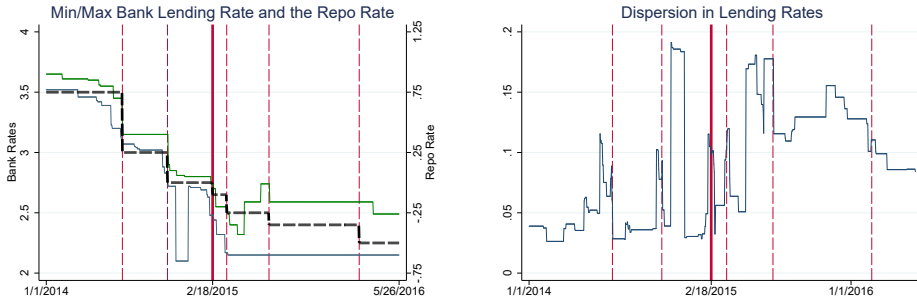
Figure 4.7: Lending rates by Swedish banks. Left panel: The solid green (blue) line depicts the maximum (minimum) bank lending rate, while the dashed black line depicts the repo rate. Right panel: Left Cross-sectional standard deviation in lending rates Sweden. Interest rate on five-year mortgages.

What is causing the increase in dispersion in banks responses to policy rate cuts? One theory is that differences in the reliance on deposit financing means that banks are being differentially affected by negative interest rates. Given that there are frictions in raising different forms of financing - and some sources of financing are more responsive to monetary policy changes than others - cross-sectional variation in balance-sheet components can induce variation in how monetary policy affects banks (Kashyap and Stein, 2000). This is especially relevant in our setting. Negative interest rates have had a more limited pass-through to deposit financing relative to other sources of financing. To investigate whether bank's funding structures affect their willingness to lower lending rates, we plot the bank level correlation between lending rates and the repo rate after the repo rate turned negative, as a function of bank's deposit shares. The result is depicted in Figure 4.8. As is clear from the figure, there is a negative relationship between the deposit share and the correlation with the repo rate. That is, banks with higher deposit shares are less responsive to policy rate cuts in negative territory. Weighting observations by market shares, this relationship is statistically significant at the one percent level. The regression line indicates that a 10 percentage points increase in the deposit share is associated with a reduction in the correlation of approximately 0.17 correlation points.[9]

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[9]Although average correlations drop across all fixed interest-rate periods, the increase in dispersion is most prevalent across longer fixed-rate periods. Hence, for shorter fixed-rate periods there is not enough variation in the correlations with the repo rate to precisely estimate how it depends on the deposit share.
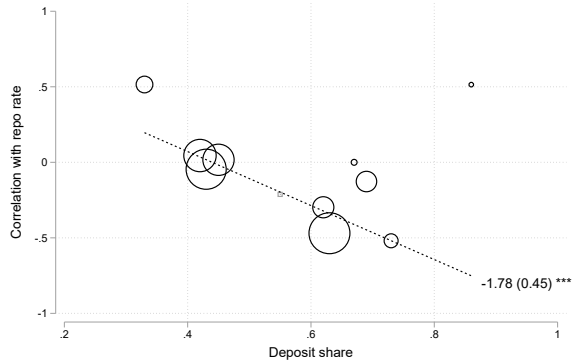
Figure 4.8: Correlation between lending rate and repo rate after the repo rate turned negative and the deposit rate reached its lower bound, as a function of the bank's deposit share. Size of circles indicate market share. Gray square indicates Ålandsbanken, for which we do not have the market share. Regression coefficient (standard error) also reported. $***$ indicates $p < 0.01$. Swedish banks. Interest rate on 5 year mortgages.

So far we have investigated what happens to bank interest rates, or prices. An alternative approach is to instead consider quantities, or bank lending volumes. This is the approach adopted in Heider, Saidi, and Schepens (2016) for Euro Area banks. Consistent with our proposed explanation, they find that banks with higher deposit shares had lower lending growth after the policy rate turned negative. Here we show that this result also holds for Swedish banks. Following Heider, Saidi, and Schepens (2016) we use the difference in difference framework specified in equation (4.1). The dependent variable is the (approximate) percentage 3-month growth in bank level lending. I_t^{post} is an indicator variable equal to one after the policy rate became negative, while Deposit share$_i$ is the deposit share of bank i in year 2013. As an alternative specification, we replace Deposit share$_i$ with an indicator $\mathbb{1}_{\text{High deposit share}}$ for whether bank i has a deposit share above the median in 2013. We include bank fixed effects δ_i to absorb time-invariant bank characteristics, and month-year fixed effects δ_t to absorb shocks common to all banks. Standard errors are clustered at the bank level. We restrict our sample to start in 2014, following Heider, Saidi, and Schepens (2016) in choosing a relatively short time period around the event date. The coefficient of interest is the interaction coefficient β. If banks with high deposit shares have lower credit growth than banks with low deposit shares after the policy rate breaches the zero lower bound, we expect to find $\hat{\beta} < 0$.[10]

$$\Delta \log(\text{Lending}_{i,t}) = \alpha + \beta \left(I_t^{\text{post}} \times \text{Deposit share}_i \right) + \delta_i + \delta_t + \epsilon_{it} \tag{4.1}$$

The regression results are reported in Table 4.2. Focusing on column (1) first, the interaction coefficient is negative as expected, and significant at the five percent level. An increase in the deposit

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[10]In a previous version of the paper, we used 1-month growth in bank-level lending instead of 3-month growth. In both cases our coefficient estimates are negative and statistically signficant. However, using 3-month growth rates is more consistent with the analysis in Heider, Saidi, and Schepens (2016) based on quarterly data, and increases our precision slightly.

share is associated with a reduction in credit growth at the bank level. Stated differently, credit growth in the post-zero environment is significantly lower for banks which rely heavily on deposit financing. The effect is economically significant - a one standard deviation increase in the deposit share decreases lending growth by approximately 0.18 standard deviations.

In column (2) we look at the average growth in credit for high deposit share banks relative to low deposit share banks in the post-zero environment. While we lose some precision by using only an indicator variable, the coefficient is still negative and statistically significant at the ten percent level. On average, banks with a high deposit share had four percentage points lower growth in credit compared to banks with a low deposit share. We thus conclude that, due to the lower bound on the deposit rate, banks which rely heavily on deposit financing are less responsive to policy rate cuts in negative territory. The cross-sectional evidence presented here, is consistent with the survey evidence in Figure 4.9 where the vast majority of European banks report that they have not increased lending volumes in response to negative policy rates.

Dependent variable:	$\Delta \log\left(Lending\right)_{i,t}$	
	(1)	(2)
$I_t^{\text{post}} \times \text{Deposit share}_i$	-0.08^{**}	
	(-2.09)	
$I_t^{\text{post}} \times \mathbb{1}_{\text{High deposit share}_i}$		-0.04^{*}
		(-1.85)
Clusters	40	40
Bank FE	Yes	Yes
Month-Year FE	Yes	Yes
Observations	1113	1113

Table 4.2: Regression results from estimating equation (4.1). Dependent variable: $\Delta \log\left(\text{Lending}\right)_{i,t} \equiv \log\left(Lending\right)_{i,t} - \log\left(\text{Lending}\right)_{i,t-3}$. Monthly bank level data from Sweden. $^{**}p < 0.05$, $^{*}p < 0.1$.

Unchanged or decreased lending volumes (%)

Loans to enterprises
Loans to households

2016Q2   2016Q4   2017Q2   2017Q4
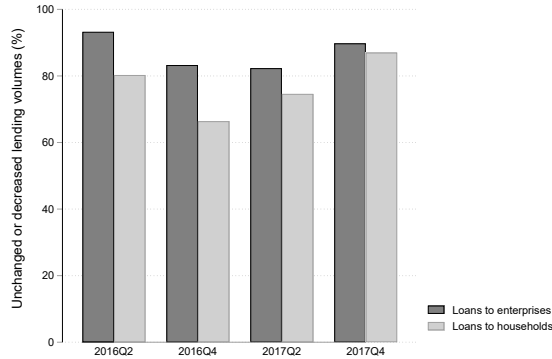
Figure 4.9: Share of banks answering that the negative ECB policy rate has had a negative or neutral effect on their lending volume in the past six months. Household loans only include loans to house purchases. Source: ECB bank lending survey.

Overall funding costs   It is possible that the effective deposit rate has fallen more than the nominal deposit rate. This would be the case if banks have responded to negative interest rates by increasing fees. We think this is of limited quantitative importance for two reasons. First, if the lower bound is due to the existence of money as a store of value, there is no reason to believe that the effective deposit rate should not be subject to the same lower bound. Second, as we show in Figure 4.10 aggregate commission income for Swedish banks did not increase following the introduction of negative policy rates.

Net Commission Income as a Share of Assets (%)

1995   2000   2005   2010   2015
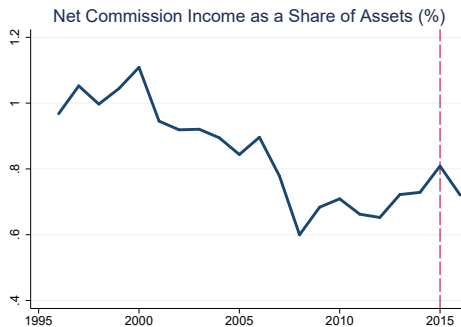
Figure 4.10: Net commission income as a share of total assets for swedish banks. Source: Statistics Sweden.

The empirical analysis so far has centered around the link between deposit rates and lending rates. However, banks also use other financing sources. In the left panel of Figure 4.11 we show the composition of liabilities for Swedish banks. Deposits account for almost half of banks total

financing, while covered bonds accounts for almost 1/4. Remaining liabilities are accounted for by interbank loans, certificates and unsecured debt. In the right panel of Figure 4.11 we plot various other interest rates. Interbank rates, represented by STIBOR 3M, have largely followed the repo rate into negative territory. However, as net interbank lending is small in aggregate this has had limited impact on banks overall funding costs. The pass-through of negative rates to long-term covered bonds appears substantially weakened. Interest rates on short-term covered bonds, however are slightly negative.
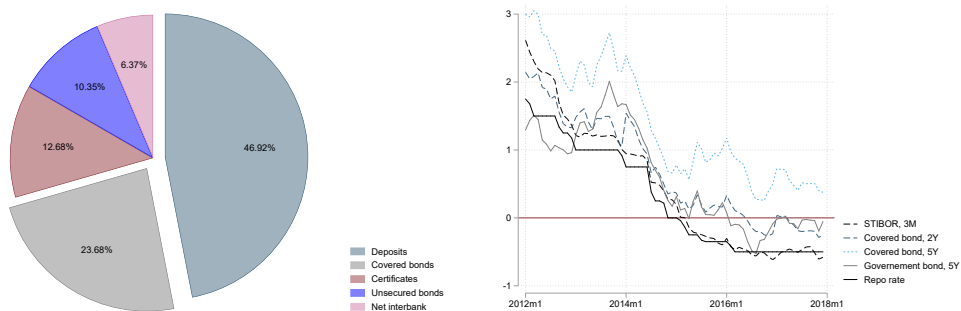
Figure 4.11: Left panel: Decomposition of liabilities (as of September 2015) for large Swedish banks. Right panel: Other interest rates. Sweden. Source: Riksbank

What does this imply for overall funding costs? In Figure 4.12 we plot an estimate of the average funding costs for Swedish banks over time. The estimate is the weighted average of the interest rates on the various liabilities of Swedish banks. For those liabilities where we do not observe the interest rate (unsecured debt and certificates), we assume that the pass-through equals the pass-through to short-term covered bonds. Because the pass-through to short-term covered bonds has been fairly strong we view this as an conservative assumption.[11] As is clear from the figure, the sensitivity of total average financing costs to the policy rate appears substantially weakened once the policy rate goes negative. This is the result of the sharp reduction in the pass-through to the two largest financing sources for Swedish banks, deposits and covered bonds.

To illustrate the reduction in pass-through, we construct a counterfactual funding cost where the markup relative to the repo rate equals the average markup in the pre-zero period. Our estimate suggests that if there had not been a decline in pass-through, the average funding cost for Swedish banks would be slightly negative, compared to approximately 0.25 percent today.

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[11]An even more conservative assumption would be assuming full pass-through. In Appendix C.1, we construct an alternative estimate based on this assumption. Although the pass-through becomes slightly larger in this case, the decline in pass-through is still striking.
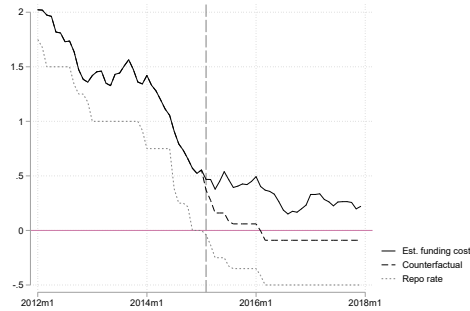
Figure 4.12: Estimated average funding costs. The estimated average funding cost is computed by taking the weighted average of the assumed interest rate of the different funding sources of the bank. Certificates are assumed to have the same interest rate as 2Y covered bonds, while unsecured debt are assumed to have the same interest rate as 2Y covered bonds plus a 2 percent constant risk-premium. The "counterfactual" series correspond to the case when the spread between the repo rate and the estimated funding cost remain fixed at pre-negative levels. Weights based on the liability structure of large Swedish banks, see Figure 4.11.

The estimated funding cost is based on the preexisting liability structure of Swedish banks, however. One could imagine that Swedish banks altered their liability structure in response to negative rates - for example by reducing their reliance on deposit financing. This is an important question in determining the *marginal* funding cost of banks. In the left panel of Figure 4.13, we plot new issuances of covered bonds - the most important non-deposit financing source. There does not appear to have been an increase in covered bond issuances after the repo rate went negative. Perhaps surprisingly, the right panel of Figure 4.13 depicts an *increase* in deposit financing in the post-zero environment.
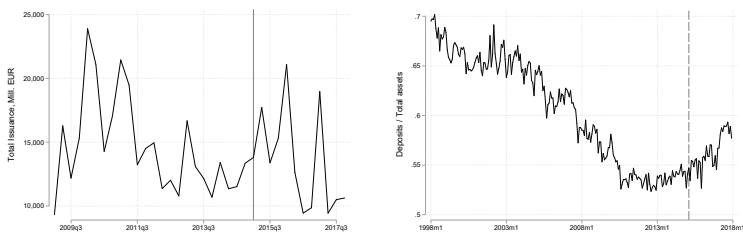
Figure 4.13: Left panel: Issuance of covered bonds, Swedish banks. Right panel: Deposit share, Swedish banks. Vertical lines correspond to the date negative interest rates were implemented. Source: Association of Swedish Covered Bond Issuers, Riksbank and Statistics Sweden

Why do Swedish banks remain reliant on deposit financing, despite their relatively high cost? There are at least three possible explanations: i) maintaining a base of depositors creates some synergies which other financing sources do not, ii) the room for new issuances of covered bonds

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may be limited by the availability of bank assets to use for collateral, iii) Basel III regulation makes deposit financing more attractive in terms of satisfying new requirements. We do not take a stand on *why* banks have increased their deposit financing, but note that the empirical evidence suggests that deposit rates are the most important component of, not only average, but also *marginal* funding costs. In our model we therefore make the simplifying assumption that deposits is the only financing source.

4.3   Negative interest rates in theory

Motivated by the empirical facts outlined in the previous section, we now develop a formal framework for understanding the impact of negative central bank policy rates.

4.3.1   Model

To theoretically analyze how effective negative interest rates are in terms of stabilizing inflation and output, we set up a New Keynesian (NK) model. Several parts of the model are standard in the literature, and a detailed discussion and derivation of the full set of equilibrium conditions is relegated to Appendix C.2. In this section, we provide an overview of the main elements and discuss how the log-linearized version of our model can be seen as a generalization of the standard New Keynesian model with an endogenous natural rate of interest. A key new element is explicit account of interest on reserves, a separate bound on the deposit rate that affects funding costs, a relationship between bank net worth and funding costs, and an explicit account of the ZLB due to the existence of money as store of value.

The model consists of four main parts. First, there is a household sector in which households differ in their time preferences. In equilibrium, patient households are savers, and impatient households are borrowers. In the main text we focus on the money demand part of the household problem, as this gives rise to the lower bound on the deposit rate. The second building block of the model is the firm sector, which builds heavily on Benigno, Eggertsson, and Romei (2014). Firms produce using labor and face price rigidities in the form of Calvo pricing. Because the firm problem is standard we do not discuss it further in the main text. The third part of our model is the bank sector. This is a crucial part of our model, and contains mostly novel elements. Accordingly we outline the bank problem in some detail below. Finally, we introduce central bank reserves and outline the necessary assumptions about policy to close the model.

Households demand for money and the lower bound

Household $j \in \{s, b\}$ consumes, holds money, saves and supplies labor. Households of type s are savers, while households of type b are borrowers. We let $\Omega\left(\dfrac{M_t^j}{P_t}\right)$ denote the utility from holding

real money balances.[12] $U\left(C_t^j\right)$ denotes the utility of consumption and $S\left(M_t^j\right)$ denotes the storage cost of holding money. Furthermore, let i_t^j be the interest rate that an agent of type j faces. In our set-up, optimal money holdings have to satisfy

$$\frac{\Omega'\left(\dfrac{M_t^j}{P_t}\right)}{U'\left(C_t^j\right)} = \frac{i_t^j + S'\left(M_t^j\right)}{1 + i_t^j} \tag{4.2}$$

Households demand for money depends on the marginal utility from holding money, as well as the marginal cost. The latter depends not only on the opportunity cost of lost interest income, but also on the marginal storage cost $S'\left(M_t^j\right)$. The lower bound on the deposit rate $\underline{i}^s$ is typically defined as the lowest value of i_t^s satisfying equation (4.2). The lower bound therefore depends crucially on the marginal storage cost. We assume proportional storage cost $S\left(M_t^s\right) = \gamma M_t^s$, which implies a lower bound on the deposit rate of $\underline{i}^s = -\gamma$ (as $\Omega'\left(\dfrac{M_t^j}{P_t}\right) = 0$ when households are satiated in real money balances). This allows for the possibility that the lower bound is negative ($\gamma > 0$), and also nests the case of a lower bound at exactly zero ($\gamma = 0$).

The role of banks

Our banking sector is made up of identical, perfectly competitive banks. Bank assets consist of one-period real loans l_t. In addition to loans, banks hold real reserves $R_t \geq 0$ and real money balances $m_t = \dfrac{M_t}{P_t} \geq 0$, both issued by the central bank.[13] Bank liabilities consist of real deposits d_t. Reserves are remunerated at the interest rate i_t^r, which is set by the central bank. Loans earn a return i_t^b. The cost of funds, i.e. the deposit rate, is denoted i_t^s. Banks take all of these interest rates as given.

Financial intermediation takes up real resources. Therefore, in equilibrium, there is a spread between the deposit rate i_t^s and the lending rate i_t^b. We assume that bank's intermediation costs are given by a function $\Gamma\left(\dfrac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right)$, where $z_t = \dfrac{Z_t}{P_t}$ is real bank profits. In order to allow for the intermediation cost to be time-varying for a given set of bank characteristics, we include a stochastic cost-shifter $\bar{l}_t$. This cost-shifter may capture time-variation in borrowers default probabilities, changes in the borrowing capacity, bank regulation etc. (Benigno, Eggertsson, and Romei, 2014).

We assume that the intermediation cost is increasing and convex in the amount of real loans provided. That is, $\Gamma_l > 0$ and $\Gamma_{ll} \geq 0$. Central bank currency plays a key role in reducing intermediation costs.[14] The marginal cost reductions from holding reserves and money are captured

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[12] We assume a satiation point for money. That is, at some level $\bar{m}^j$ households become satiated in real money balances, and so $\Omega'(\bar{m}^j) = 0$.

[13] Because we treat the bank problem as static - as outlined below - we can express the maximization problem in real terms.

[14] For example, we can think about this as capturing in a reduced form way the liquidity risk that banks face. When banks provide loans, they take on costly liquidity risk because the deposits created when the loans are made have a stochastic point of withdrawal. More reserves helps reduce this expected cost.

by $\Gamma_R \leq 0$ and $\Gamma_m \leq 0$ respectively. We assume that the bank becomes satiated in reserves for some level $\bar{R}$. That is, $\Gamma_R = 0$ for $R \geq \bar{R}$. Similarly, banks become satiated in money at some level $\bar{m}$, so that $\Gamma_m = 0$ for $m \geq \bar{m}$. Banks can thus reduce their intermediation costs by holding reserves and/or cash, but the opportunity for cost reduction can be exhausted. Finally, we allow for the possibility that higher profits may reduce the marginal cost of lending. That is, we assume $\Gamma_{lz} \leq 0$. We discuss this assumption below.

Following Curdia and Woodford (2011) and Benigno, Eggertsson, and Romei (2014) we assume that any real profits from the bank's asset holdings are distributed to their owners in period t and that the bank holds exactly enough assets at the end of the period to pay off the depositors in period $t+1$.[15] Furthermore, we assume that the bank has the same storage costs of money as the household sector. Under these assumptions, real bank profits can be implicitly expressed as:

$$z_t = \frac{i_t^b - i_t^s}{1 + i_t^s} l_t - \frac{i_t^s - i_t^r}{1 + i_t^s} R_t - \frac{i_t^s + \gamma}{1 + i_t^s} m_t - \Gamma\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right) \tag{4.3}$$

Any interior l_t, R_t and m_t have to satisfy the respective first-order conditions from the bank's optimization problem[16]

$$l_t \quad : \quad \frac{i_t^b - i_t^s}{1 + i_t^s} = \frac{1}{\bar{l}_t}\Gamma_l\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right) \tag{4.4}$$

$$R_t \quad : \quad -\Gamma_R\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right) = \frac{i_t^s - i_t^r}{1 + i_t^s} \tag{4.5}$$

$$m_t \quad : \quad -\Gamma_m\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right) = \frac{i_t^s + \gamma}{1 + i_t^s} \tag{4.6}$$

The first-order condition for real loans says that banks trade off the marginal income from lending with the marginal increase in intermediation costs. The next two first-order conditions describe banks demand for reserves and cash. We assume that reserves and money are not perfect substitutes, and so minimizing the intermediation cost implies holding both reserves and money.

The first-order condition for loans pins down the equilibrium credit spread ω_t, defined as

$$\omega_t \equiv \frac{1 + i_t^b}{1 + i_t^s} - 1 = \frac{i_t^b - i_t^s}{1 + i_t^s} \tag{4.7}$$

Specifically, if borrowers are of measure χ, the equilibrium credit spread is

$$\omega_t = \frac{1}{\chi \bar{b}_t}\Gamma_l\left(\frac{b_t^b}{\bar{b}_t}, R_t, m_t, z_t\right) \tag{4.8}$$

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[15]The latter is equivalent to assuming that $\left(1 + i_t^b\right) l_t + \left(1 + i_t^r\right) R_t + m_t - S\left(m_t\right) = \left(1 + i_t^s\right) d_t$.

[16]Assuming that $\Gamma\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right)$ is such that there exists a unique z solving equation (4.3).

where we have used the market clearing condition $l_t = \chi b_t^b$ to express the spread as a function of the borrowers real debt holdings b_t^b.[17] That is, the difference between the borrowing rate and the deposit rate is an increasing function of the aggregate relative debt level, and a decreasing function of bank profits.

Why do bank profits affect intermediation costs? We have allowed for the possibility that the marginal cost of extending loans decreases in bank profits. That is, $\Gamma_{lz} \leq 0$. This assumption captures, in a reduced form manner, the established link between bank's net worth and their operational costs - assuming there is a one-to-one mapping between net worth and profits. We do not make an attempt to microfound this assumption, which is explicitly done in among others Holmstrom and Tirole (1997) and Gertler and Kiyotaki (2010), as well as documented empirically in for instance Jiménez, Ongena, Peydró, and Saurina (2012).[18][19]

If $\Gamma_{lz} = 0$, there is no feedback effect from bank profits to credit supply. Note that this does not change the main result that negative interest rates are *not expansionary*, but it implies that there is not contractionary effect of negative interest rates. Because there has been widespread concern that negative interest rates would hurt bank profitability and thereby dampen credit supply (see for instance Waller (2016) and Financial Times (2016)), we also allow for the possibility that $\Gamma_{lz} < 0$.

Policy

To close the model, we need to be explicit about policy. The central bank in our model sets the interest rate on reserves i_t^r and chooses the total supply of central bank currency in order to ensure that $i_t^s = i_t^r$ whenever possible.[20] From the first order condition for reserves (4.5), we see that $i_t^s = i_t^r$ implies that $\Gamma_R = 0$. Hence, as long as banks are satiated in reserves, the central bank implicitly controls i_t^s via i_t^r. A key point however, is that $\Gamma_R = 0$ is not always feasible due to the lower bound on the deposit rate. If the deposit rate is bounded at $\underline{i}^s = -\gamma$, and the central bank lowers i_t^r below $-\gamma$, then $i_t^s > i_t^r$. The first order condition then implies $\Gamma_R > 0$. Intuitively, it is not possible to keep banks satiated in reserves when they are being charged for their reserve holdings. More explicitly, we assume that the interest rate on reserves follows a Taylor rule given by equation (4.9). Because of the reserve management policy outlined above, the deposit rate in equilibrium is either equal to the reserve rate or to the lower bound, as specified in equation (4.10).

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[17]We also assume that $\bar{l}_t = \chi \bar{b}_t$.

[18]Another way to interpret the implied link between bank profits and credit supply is to include a capital requirement. In Gerali, Neri, Sessa, and Signoretti (2010) a reduction in bank profits reduces the bank's capital ratio. In order to recapitalize the bank lowers credit supply.

[19]Alternatively, we could assume that bank profits do not affect intermediation costs, but that bank profits are distributed to all households. A reduction in bank profits would then reduce aggregate demand through the borrowers budget constraint.

[20]This policy regime is consistent with a "floor-system" of monetary policy, which has been implemented in many countries, including the U.S, after the crisis. Our model allows us to also analyze a pre-crisis policy regime, in which central banks pay no interest on reserves, so that $i_t^r = 0$. Under such a regime, the policy maker then chooses central bank currency so as to ensure that the risk-free rate is equal to its target.

$$i_t^r = r_t^n \Pi_t^{\phi_\pi} Y_t^{\phi_Y} \tag{4.9}$$

$$i_t^s = \max\{\underline{i}^s, i_t^r\} \tag{4.10}$$

4.3.2   A generalization of the standard New Keynesian model

We take a log-linear approximation of the equilibrium conditions around the steady state, with details outlined in Appendix C.2. The steady state equations, as well as the log-linearized equilibrium conditions are summarized in the same appendix. Here we reproduce the key equations in order to make the following observation: in the absence of interest rate bounds, and any shocks that create a trade-off between inflation and output, our model reduces to the standard New Keynesian model. The central bank can replicate a zero inflation target and keep output at its natural level at all times. Our log-linearized model is therefore a natural generalization of the textbook New Keynesian model with an endogenous natural rate of interest. Our extension, however, goes beyond simply introducing a ZLB along with an endogenous natural rate of interest, as we will have a clear distinction between interest rates on reserves, deposit rates as well as borrowing rates. And while there is no bound on the reserve rate, the deposit rate is subject to a lower bound.

The supply side of our model can be summarized by the generic Phillips curve

$$\hat{\pi}_t = \kappa \hat{y}_t + \beta \mathbb{E}_t \hat{\pi}_{t+1} \tag{4.11}$$

The demand side is governed by the IS-curve

$$\hat{y}_t = \mathbb{E}_t \hat{y}_{t+1} - \sigma \left(\hat{i}_t^s - \mathbb{E}_t \hat{\pi}_{t+1} - \hat{r}_t^n \right) \tag{4.12}$$

In the standard model, the natural rate of interest r_t^n is exogenous. In our case the natural rate of interest is endogenous, and depends on the shocks to the economy and the agents' decisions. Specifically, letting $\hat{\zeta}_t$ denote exogenous shifts in the agents preferred time allocation of consumption, the natural rate of interest takes the following form

$$\hat{r}_t^n = \hat{\zeta}_t - \mathbb{E}_t \hat{\zeta}_{t+1} - \chi \hat{\omega}_t \tag{4.13}$$

The natural rate of interest now depends on the interest rate spread $\hat{\omega}$, which is endogenous and given by equation (4.14). Given the assumed functional form for the banks intermedation cost Γ outlined in Appendix C.2, the link between household debt and the marginal cost of lending is parameterized by $\nu > 1$. Moreover, the feedback effect from bank profits to the marginal intermediation cost is captured by the parameter $\iota \geq 0$. An increase in private debt increases the interest rate spread, thereby reducing the natural rate of interest. Similarly, a reduction in bank profits reduces the natural rate of interest if $\iota > 0$.

$$\hat{\omega}_t = \frac{i^b - i^s}{1 + i^b} \left((\nu - 1)\hat{b}_t^b - \nu \hat{\bar{b}}_t - \iota \hat{z}_t \right) \tag{4.14}$$

While the standard New Keynesian model only has one interest rate, our model has three distinct interest rates. We have an interest rate on borrowing i_t^b, as well as an interest rate on savings i_t^s. In addition we also have an interest rate on central bank reserves i_t^r. The log-linearized reserve rate is set by the central bank according to a standard Taylor rule

$$\hat{i}_t^r = \hat{r}_t^n + \phi_\pi \hat{\pi}_t + \phi_y \hat{y}_t \tag{4.15}$$

Because the central bank keeps the bank sector satiated in reserves whenever feasible, the deposit rate is equal to the reserve rate when the lower bound is not binding, and is equal to the lower bound otherwise

$$\hat{i}_t^s = \max \left\{ \underline{\hat{i}}^s, \hat{i}_t^r \right\} \tag{4.16}$$

where $\underline{\hat{i}}^s = \dfrac{\beta^s}{\pi}(1 - \gamma) - 1$ is the lower bound on the deposit rate expressed in deviations from steady state. The current characterization of the model, given by equations (4.11) - (4.16) is incomplete, but we relegate to Appendix C.2 the full set of equations needed to describe the dynamics of private debt and bank profits in order to conserve space. This partial representation is however sufficient to highlight the important economic mechanisms of our model. If there is no constraint on the policy rate and we set $i_t^s = i_t^r$, then the central bank can fully offset any variations in r_t^n via the policy rate. In this case, as in the standard model, it is easy to confirm that there is an equilibrium in which $\hat{i}_t^s = \hat{i}_t^r = \hat{r}_t^n$ and $\hat{\pi}_t = \hat{y}_t = 0$, and the model reduces to the standard model.

4.3.3 Monetary policy transmission with and without negative interest rates

The characterization above also clarifies how our model provides additional details on the transmission of monetary policy via the banking system. If the central bank lowers the reserve rate in normal times, this lowers the deposit rate through equation (4.16). The reduction in the deposit rate stimulates the consumption of saver households. In addition, lowering the deposit rate reduces the banks financing costs. This increases their willingness to lend, putting downwards pressure on the borrowing rate and thereby stimulating the consumption of borrower households. Hence, the reduction in the reserve rate passes through to the other interest rates in the economy, thereby stimulating aggregate demand.

Most macro models either implicitly or explicitly assume that the economy has only one interest rate, which the central bank controls directly. This seems like an acceptable assumption in normal times. However, once the policy rate falls below the bound on the deposit rate, allowing for multiple interest rates becomes crucial. As evident from equation (4.16), lowering the reserve rate below the bound on the deposit rate and into negative territory has no effect on the deposit rate. Further, because the deposit rate stays unchanged, there is no stimulative effect on bank's financing costs

and so no increase in their willingness to lend. As a result, there is no longer a boost to aggregate demand. Moreover, because charging a negative interest rate on reserves reduces bank profits, the interest rate spread in equation (4.14) increases if $\iota > 0$. This implies an *increase* in the borrowing rate, and so aggregate demand falls. Hence, when the deposit rate is stuck at its lower bound, and there is a feedback effect from bank profits to the marginal cost of lending, further reductions in the reserve rate have a *contractionary* effect on the economy. If $\iota = 0$ on the other hand, negative interest rates are neither expansionary nor contractionary. We now illustrate these results with a numerical example.

4.4 The Effects of Monetary Policy in Positive and Negative Territory

In this section, we compare our baseline model (which we refer to as the negative reserve rates model) to two other models. The first is our variant of the standard lower bound NK model. In this case, there is an identical effective lower bound on both the deposit rate and the central banks policy rate. The second is the frictionless model, in which both the deposit rate and the central bank policy rate can fall below zero.

To analyze the dynamic transition of the three models we consider a temporary preference shock - a standard ZLB shock dating at least back to Eggertsson and Woodford (2003). The preference shock effectively makes agents more patient and so delays consumption. We then evaluate to which degree the central bank can stimulate aggregate demand by lowering the reserve rate. In Appendix C.3 we consider an alternative shock, namely a permanent reduction in the debt limit - otherwise known as a debt deleveraging shock (Eggertsson and Krugman, 2012). The qualitative implications for the effectiveness of negative interest rates do not depend on which shock we consider. We pick the size of both shocks to generate an approximate 4.5 percent drop in output on impact. This reduction in output is chosen to roughly mimic the average reduction in real GDP in Sweden, Denmark, Switzerland and the Euro Area in the aftermath of the financial crisis, as illustrated in Figure C.1 in Appendix C.1.[21] The drop in output in the US was of similar order. The persistence of the preference shock is set to generate a duration of the lower bound of approximately 12 quarters. We choose the parameters of the model from the existing literature whenever possible. A discussion of the calibration is included in Appendix C.3.

4.4.1 Preference shock

The effects of the preference shock in the three different model regimes are depicted in Figure 4.14.

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[21]Detrended real GDP fell sharply from 2008 to 2009, before partially recovering in 2010 and 2011. The partial recovery was sufficiently strong to induce an interest rate increase. We focus on the second period of falling real GDP (which occurred after 2011), as negative interest rates were not implemented until 2014-2015. Targeting a reduction in real GDP of 4.5 percent is especially appropriate for the Euro Area and Sweden. Real GDP fell by somewhat less in Denmark, and considerably less in Switzerland. This is consistent with the central banks in the Euro Area and Sweden implementing negative rates because of weak economic activity, and the central banks in Denmark and Switzerland implementing negative rates to stabilize their exchange rates.

We start by considering the completely frictionless case, referred to as the *No bound* case. In this scenario it is assumed that both the policy rate and the deposit rate can turn negative, as illustrated by the dashed black lines in Figure 4.14.

The preference shock reduces aggregate demand and inflation, triggering an immediate response from the central bank. In the absence of bounds the central bank can hold banks satiated in reserves, and so the reduction in the reserve rate leads to an identical reduction in the deposit rate. The reduction in the deposit rate reduces bank's financing costs, increases lending and thereby stimulating the consumption of both borrowers and savers.

Contrast the frictionless case to the standard case, in which both the policy rate and the deposit rate are bounded. In this case, the central bank is not able to offset the shock, and output falls below its steady state value. This scenario is outlined by the solid black lines in Figure 4.14. The key reason is that the central bank is unable to reduce the deposit rate below it's lower bound and hence also increase lending. Thus, the expansionary effect on borrowers and savers are muted relative to the frictionless case.

Finally, we consider the case deemed to be most relevant to what we see in the data. While the policy rate is not bounded, there exists an effective lower bound on the deposit rate. This case is illustrated by the red dashed lines in Figure 4.14.
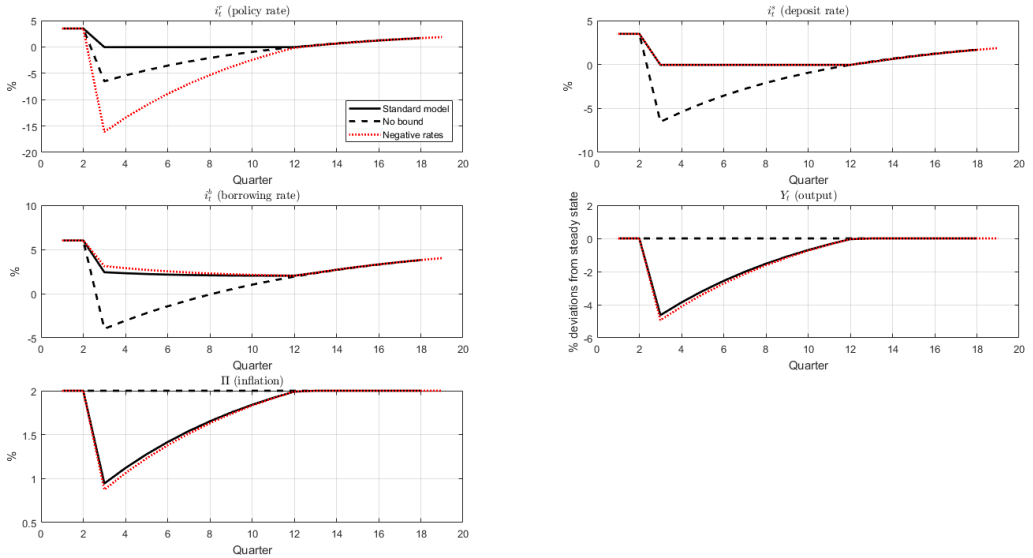
Figure 4.14: Impulse response functions following an exogenous decrease in the marginal utility of consumption (ζ_t), under three different models. *Standard model* refers to the case where there is an effective lower bound on both deposit rates and the central bank's policy rate. *No bound* refers to the case where there is no effective lower bound on any interest-rate. *Negative rates* refers to the model outlined above, where there is an effective lower bound on the deposit rate but no lower bound on the policy rate.

The central bank reacts to the shock by aggressively reducing the policy rate.[22] However, the deposit rate only responds until it reaches its lower bound, at which point it is stuck. As a result, the borrowing rate does not fall as much as in the frictionless case, and the central bank is once again unable to mitigate the negative effects of the shock on aggregate demand and inflation.

Output declines more in the negative scenario compared to the standard case. The reason is the negative effect on bank profits resulting from the negative interest rate on reserves. Banks hold reserves in order to reduce their intermediation cost, but when the policy rate is negative they are being charged for doing so. At the same time, their financing costs are unresponsive due to the lower bound on the deposit rate. Hence, bank profits are lower when the policy rate is negative.[23]

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[22]This reaction is exaggerated by our assumption that the central bank literally follows the Taylor rule in setting the interest rate on reserves, while in practice central banks only experimented with modestly negative rates.

[23]The fall in bank profits is large in our case, and profits become negative in the negative reserve rate model. The reason is that the central bank follows the Taylor rule and sets the reserve rate equal to - 17 % in an unsuccessful effort to mitigate the shock. This is an extreme policy compared to the recent experience with negative interest rates, in which interest rates are only modestly below zero. As of mid-February 2016, the effective policy rate in Denmark, the Euro Area, Sweden and Switzerland ranged between -25 to -52 basis points (Bech and Malkhozov, 2016). Given the outstanding reserves in these countries, the loss from negative policy rates (relative to a reserve rate of 0 %) corresponds to approximately 0.7 - 1.8 billion in domestic currencies, which is approximately 0.12 % - 0.51 % of the domestic banking sectors equity.

If $\iota > 0$, this decline in bank profits feeds back into aggregate demand through the effect of bank net worth on the marginal lending cost. Lower net worth increases the cost of financial intermediation, which reduces credit supply and dampens the pass-through of the policy rate to bank's lending rates.

The importance of profits for banks intermediation costs is parameterized by ι. In Table 4.3 we report the effect on output and the borrowing rate for different assumptions about ι. In the case in which there is no feedback from bank profits to intermediation costs ($\iota = 0$), the output drop under negative rates corresponds to the output drop under the standard model. The same holds for the borrowing rate. As ι increases, the reduction in the borrowing rate is muted due to the increase in intermediation costs. As a result, output drops by more. For a sufficiently high ι, the borrowing rate actually *increases* when negative policy rates are introduced. This is consistent with the bank-level data on daily interest rates from Sweden, where some banks in fact *increased* their lending rate following the introduction of negative interest rates. Bech and Malkhozov (2016) and Basten and Mariathasan (2018) report a similar increase in lending rates in Switzerland.

Model	Output, % deviation from SS	Borrowing rate, percentage points change
Standard	- 4.5	- 3.5
$\iota = 0$	- 4.5	- 3.5
$\iota = 0.1$	- 4.7	- 3.3
$\iota = 0.15$	- 4.8	- 3.1
$\iota = 0.2$	- 4.9	- 2.9
$\iota = 0.25$	- 5.0	- 2.7
$\iota = 0.5$	- 5.7	- 1.1
$\iota = 0.7$	- 6.9	1.6

Table 4.3: The effect of a preference shock on output and the borrowing rate (on impact) with negative policy rates for different values of ι. The first row reports the outcomes under the standard model for comparison.

To summarize, negative interest rates are not expansionary relative to the case in which the policy rate is not set below zero. In fact, when $\iota > 0$ there is an additional dampening effect on aggregate demand, making negative interest rates contractionary.

4.5   Discussion

In our model exercise, the storage cost of money was held fix. However, one could allow the storage cost of money to depend on policy. To the extent that the presence of money is the driving force behind the observed lower bound on deposit rates, affecting the storage cost of money can affect the central bank's ability to stimulate aggregate demand. There are several ways in which this can be done. The oldest example is a tax on currency, as outlined by Gesell (1916). Gesell's idea would show up as a direct reduction in the bound on the deposit rate in our model, thus giving the central bank more room to lower the interest rate on reserves - and the funding costs of banks. Another

possibility is to ban higher denomination bills, a proposal discussed in among others Rogoff (2017c). To the extent that this would increase the storage cost of money, this too, should reduce the bound on the banks deposit rate. An even more radical idea, which would require some extensions to our model, is to let the reserve currency and the paper currency trade at different values. This proposal would imply an exchange rate between electronic money and paper money, and is discussed in Agarwal and Kimball (2015), Rogoff (2017a) and Rogoff (2017b). A key pillar of the proposal – but perhaps also a challenge to implementability – is that it is the reserve currency which is the economy wide unit of account by which taxes are paid, and accordingly what matters for firm price setting. If such an institutional arrangement is achieved, then there is nothing that prevents a negative interest rate on the reserve currency while cash in circulation would be traded at a different price, given by an arbitrage condition. The take-away from the paper should not be that negative nominal rate are always non-expansionary, simply that they are likely to be so under the current institutional arrangement. This gives all the more reason to contemplate departures from the current framework, such as those mentioned briefly here and discussed in detail by the given authors.

We conclude this paper by discussing some arguments put forward by proponents of negative interest rates. Addressing all of these arguments formally would require expanding our model substantially. Instead, we elaborate informally on whether we believe any of these changes would alter our main conclusions.

Bank Fees While banks have largely been unwilling to lower their deposit rates below zero, there has been some discussion surrounding their ability to make up for this by increasing fees and commission income. In our model there are no fixed costs involved in opening a deposit account, but allowing for this would imply that the interest rate on deposits could exceed the effective return on deposits. If banks respond to negative policy rates by increasing their fees, this could in principle reduce the effective deposit rate, and thereby lower bank's funding costs. However, as illustrated in Figure 4.10, the commission income of Swedish banks as a share of total assets actually fell after the policy rate turned negative. Hence, the aggregate data does not support the claim that the effective deposit rate is in fact falling. Given that depositors understand that higher fees reduce the effective return on their savings, this is perhaps not surprising. In any event, the ability to store money should ultimately put a bound on the banks ability to impose fees.

Alternative Transmission Mechanisms Our focus is on the effect of monetary policy on bank interest rates. When the policy rate is positive, lowering it reduces the interest rates charged by banks, which increases credit supply and thereby economic activity. We have shown that this mechanism is weakened once the policy rate turns negative. However, it is still possible that negative interest rates stimulate aggregate demand through other channels. Both the Swiss and Danish central banks motivated their decision to implement negative central bank rates by a need to stabilize the exchange rate. This open economy dimension of monetary policy is absent from our analysis. The point we want to make is that the pass-through to bank interest rates - traditionally the most important channel of monetary policy - is not robust to introducing negative policy rates.

Even if lending volumes do not respond to negative policy rates, there could potentially be an effect on the composition of borrowers. It has been suggested that banks may respond to negative interest rates by increasing risk taking. This could potentially increase lending rates, resulting in upward pressure on the interest rate margin. Heider, Saidi, and Schepens (2016) find support for increased risk taking in the Euro Area, using volatility in the return-to-asset ratio as a proxy for risk taking. According to their results, banks in the Euro Area responded to the negative policy rate by increasing return volatility. This is certainly not the traditional transmission mechanism of monetary policy, and it is unclear whether such an outcome is desirable.

Other policies   Our model exercise focuses exclusively on the impact of negative policy rates.[24] Other monetary policy measures which occurred over the same time period are not taken into account. This is perhaps especially important to note in the case of the ECB, which implemented its targeted longer-term refinancing operations (TLTROs) simultaneously with lowering the policy rate below zero. Under the TLTRO program, banks can borrow from the ECB at attractive conditions. Both the loan amount and the interest rate are tied to the bank's loan provision to households and firms. The borrowing rate can potentially be as low as the interest rate on the deposit facility, which is currently -0.40 percent.[25] Such a subsidy to bank lending is likely to affect both bank interest rates and bank profits, and could potentially explain why lending rates in the Euro Area have fallen more than in other places once the policy rate turned negative.

4.6   Concluding comments

Since 2014, several countries have experimented with negative policy rates. In this paper, we have documented that negative central bank rates have not been transmitted to aggregate deposit rates, which remain stuck at levels close to zero. As a result, aggregate lending rates remain elevated as well. Using bank level data from Sweden, we documented a disconnect between the policy rate and lending rates, once the policy rate fell below zero. We further showed that this disconnect was partially explained by reliance on deposit financing. Consistent with this, we found that Swedish banks with high deposit shares cut back on lending relative to other banks - once the policy rate turned negative.

Motivated by our empirical findings, we developed a New Keynesian model with savers, borrowers, and a bank sector. By including money storage costs and central bank reserves, we captured the disconnect between the policy rate and the deposit rate at the lower bound. In this framework we showed that a negative policy rate was at best irrelevant, but could potentially be contractionary

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[24]It is worth mentioning that in our model all reserves earn the same interest rate. In reality, most central banks have implemented a tiered remuneration scheme, in which case the marginal and average reserve rates differ. For example, some amount of reserves may pay a zero interest rate, while reserves in excess of this level earn a negative rate. Allowing for more than one interest rate on reserves would not qualitatively alter our results, but would be relevant for a more detailed quantitative assessment.

[25]In our model we only consider a negative interest rate on bank assets, as we impose $R \geq 0$. The TLTRO program implies a negative interest rate on a bank liability.

due to a negative effect on bank profits.

Given the long-term decline in interest rates, the need for unconventional monetary policy is likely to remain high in the future. Our findings suggest that negative interest rates are not an effective tool in fighting off the next recession. The questions remains however, what is? Alternative monetary policy measures include quantitative easing, forward guidance and credit subsidies such as the TLTRO program implemented by the ECB. While existing literature has made progress in evaluating these measures, the question of how monetary policy should optimally be implemented in a low interest rate environment remains largely unresolved.

Chapter 5

Risk-weighted capital requirements and portfolio rebalancing

with Ella Getz Wold

5.1 Introduction

Bank regulation has been high on the policy agenda since the financial crisis. An important component of the post-crisis policy reforms has been higher capital requirements for banks. The EU is scheduled to fully implement the Basel III regulation on capital requirements by 2019, and several member countries have already started increasing required capitalization levels. Similar policies have been adopted in the US, and further amendments are being discussed on both sides of the Atlantic.[1] In order to understand how capital requirements affect not only the bank sector, but also the broader economy, it is crucial to identify through which channels banks react to stricter regulation. Banks can respond not only by increasing equity, but also by reducing risk-weighted assets. While the former has been referred to as good deleveraging (Gropp, Mosk, Ongena, and Wix 2018), the latter is likely to adversely affect at least some sectors of the economy.

Capital requirements for Norwegian banks increased substantially in 2013.[2] Low-capitalized banks had to increase their capitalization levels in order to fulfill the new requirements. High-capitalized banks on the other hand, were not directly affected. As a result, ample cross-sectional variation in capital ratio growth rates emerged. At the same time, many Norwegian banks suddenly reduced their corporate credit growth. A closer look at the data reveals that this reduction in credit supply was entirely accounted for by the low-capitalized banks - which had to increase their capital ratios following the reform. To illustrate the divergence that took place in 2013, we plot corporate credit growth for low-capitalized and high-capitalized banks in Figure 5.1. The picture

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[1]See for example The Minneapolis Plan to End Too Big to Fail (November 2016), The Financial CHOICE Act (2016) and discussions surrounding a new Basel accord.

[2]The 2013 reform was the Norwegian implementation of Basel III - which constitutes changes to both capital and liquidity regulation. An advantage of studying the Norwegian reform in 2013 is that it only incorporated changes to the capital requirements. We discuss this in more detail in Section 5.2.1.

is striking. While low-capitalized and high-capitalized banks look virtually identical prior to the reform, there is a large gap opening up as capital requirements are increased in early 2013. The less affected high-capitalized banks keep their credit growth roughly constant, while credit growth for low-capitalized banks plummets to negative levels. This divergence suggests that banks which increased their capital ratios due to the reform did so, at least partly, by reducing credit growth to the *firm* sector. Interestingly, credit growth to the *household* sector reveals no similar pattern. This differential effect across sectors is the main finding of the paper.
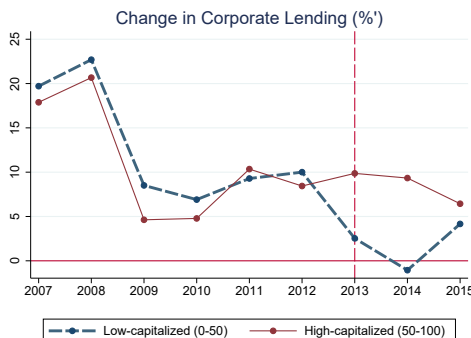
Figure 5.1: Corporate lending growth for low-capitalized and high-capitalized banks. We divide banks into groups based on their 2012 capital ratio.

We use the 2013 Norwegian policy reform to decompose the increase in capital ratios into increases in equity, reductions in total assets and reductions in average risk weights. Further, we evaluate whether changes in average risk weights can be explained by a shift from corporate lending growth to household lending growth. Finally, we look for spillover effects to the real economy in terms of employment growth.

The challenge in figuring out how banks respond to increased capital requirements is to establish an appropriate counterfactual. That is, one has to tease out how banks would have changed their equity, assets and average risk weights in absence of new regulation. The methodology we use is motivated by the striking pattern seen in Figure 5.1. Although the Norwegian requirements implemented in 2013 were levied on all banks, they affected banks differentially due to their pre-reform capital ratios. That is, low-capitalized banks had to increase their capitalization levels, whereas high-capitalized banks did not. Informally, our main identification relies on the fact that low-capitalized and high-capitalized banks look very similar prior to the reform. This is captured by the two lines in Figure 5.1 following each other closely up until 2013. In other words, high-capitalized banks seem to be an appropriate control group for low-capitalized banks. More formally, we use a flexible difference in difference methodology to identify the effect of the reform. This has two main advantages. First and most importantly, it allows us to explicitly test the standard assumption of parallel trends. For all our outcome variables, we confirm that low-capitalized and high-capitalized

banks are similar prior to the reform, ensuring that they are not on different growth trajectories. We conclude that although low-capitalized and high-capitalized banks may differ along observable dimensions, they do not differ in terms of credit growth *prior* to the reform. Secondly, the flexible difference in difference framework allows us to map out dynamic treatment effects and thereby be agnostic about the exact timing of the reform. The dynamic treatment effects are important because they allow us to also identify short-lived responses. For example, we find that banks react to higher requirements by increasing the growth in equity, but that this effect is small in size and limited to a one-year period. If we instead estimate average treatment effects over the entire post-reform period, we are not able to pick up a statistically significant effect on equity. Being agnostic about when the reform starts is also useful, as we do not have to impose a reform date explicitly, based on our priors. While the reform was implemented in the third quarter of 2013, it was announced in the first quarter of 2013. Hence, it is ex ante unclear in which quarter banks started reacting to the reform. Further, some variables are slow-moving in the sense that they are generally decided upon at the annual general assembly and apply to one calendar year at the time. These variables may start reacting only with the beginning of a new calendar year (i.e. the first quarter of 2014). By estimating dynamic treatment effects, we can let the data tell us when the reform effects occurred for different variables.

While the flexible difference in difference analysis can be done using bank level data, the loan level data enables us to achieve even tighter identification. Following Khwaja and Mian (2008) we make use of firms borrowing from more than one bank and include firm×year fixed effects in our regressions. This means that we can estimate the impact of higher capital requirements on lending to the corporate sector, while holding firm×year characteristics fixed. If one accepts that, within a given year, credit demand is determined at the firm level (and not at the loan level), this explicitly controls for any demand effects. Note that including firm×year fixed effects in our dynamic setup results in even tighter identification than the standard cross-sectional Khwaja and Mian (2008) estimator. Finally, our results are robust to including a wide range of control variables.

Our data comes from three main sources. First, we have quarterly bank level balance sheet data from The Norwegian Banks Guarantee Fund. Second, we have matched firm-bank data from the Norwegian Tax Authorities. Here we observe debt, deposits and interest paid/received for the universe of Norwegian limited liability firms and all their (domestic) bank connections. Finally, we use firm level data from a national public register to obtain employment data on the firm level.

We find that growth in equity accounts for 14 percent of the reform-induced increase in capital ratios. However, this channel is not statistically significant, as the increase in equity appears to be relatively short lived. Concentrating on the first calendar year after the reform, the impact on equity is modest in size, but statistically significant. Capital ratios are mainly increased by reducing the growth in risk-weighted assets. 38 percent of the reform-induced increase in capital ratios is due to lower growth in total assets, and 48 percent is due to a reduction in average risk weights. Hence, shifting from assets with high risk weights to assets with low risk weights is the quantitatively most important channel in explaining the increase in capital ratios following the reform.

The average risk weight on mortgage lending is 0.35 (Andersen, 2013), compared to an average risk weight of roughly 1.0 for corporate lending (Andersen and Winje, 2017). Hence, shifting credit supply from firms to households is an efficient way to reduce average risk weights. Consistent with this, we find an economically and statistically significant impact on lending growth to the corporate sector. A one percentage point higher growth rate in capital ratios is found to reduce corporate credit growth by 1.0-1.5 percentage points. We find no evidence of a reduction in household lending over the same time period, implying that low-capitalized banks are increasing their relative share of household lending. Back-of-the-envelope calculations suggest that the shift from corporate credit supply to household credit supply can account for roughly 80 percent of the reduction in average risk weights. On the loan level, we find that firms which borrow from low-capitalized banks prior to the reform have lower credit growth and lower employment growth in the post-reform period. The negative employment effect is driven by smaller firms. Consistent with the reduction in corporate credit being supply driven, we also document an increase in corporate interest rates for the low-capitalized banks.

Before discussing the existing literature, it is worthwhile to highlight some reasons why sectoral credit allocation is important. First, our results have implications for the effectiveness of the countercyclical capital buffer, which has been introduced in many countries following the financial crisis. The main goal of the capital buffer is to make banks increase their capitalization levels in good times. But it has also been suggested that the countercyclical capital buffer could potentially have a second benefit, in terms of dampening the boom in household credit (Ministry of Finance, 2016). Our results suggest that banks reduce corporate lending rather than household lending when faced with increased requirements, suggesting that any dampening effect on household credit would be limited. Note however, that our results are conditional on the current risk weights. Reducing the difference in risk weights between mortgage lending and corporate lending would probably imply that more of the reduction in credit supply would be directed towards the household sector. Second, the importance of the sectoral allocation of credit for the macro economy is not limited to credit booms. The reduction in credit to the corporate sector is found to reduce employment growth. More generally, redirecting credit from the firm sector to the household sector may have detrimental effects on the growth potential of the economy (Beck, Büyükkarabacak, Rioja, and Valev, 2012). Hence, our results highlight the importance of not only considering the impact on total credit, but also the impact on the *allocation* of credit, when discussing the design of risk-weighted capital requirements.

Literature review   Since the financial crisis, several countries have changed their capital requirements, resulting in a handful of recent papers on the topic. Brun, Fraisse, and Thesmar (2013) use variation in internal risk models among French banks, and document significant effects on corporate lending from increasing risk-weighted capital requirements. Jimenez, Ongena, Peydro, and Saurina (2017) evaluate the effect of time-varying capital requirements based on individual credit portfolios in Spain, and reach similar conclusions. Studies based on bank specific capital requirements in the UK also document significant credit supply effects (Bridges, Gregory, Nielsen, Pezzini, Radia, and

Spaltro 2014, Aiyar, Calomiris, and Wieladek 2016). De Jonghe, Dewachter, and Ongena (2016) uses idiosyncratic variation in capital requirements and find significant credit supply effects for loans with relatively high capital charges. The paper most similar to ours is perhaps Gropp, Mosk, Ongena, and Wix (2018), who use variation in capital requirements based on country-specific size cutoffs in a group of European countries. They show that banks adjust to capital requirements by reducing risk weighted assets rather than increasing equity. They find that banks in response to increased capital requirements shrink their assets, especially corporate loans.[3]

We contribute to this recent literature in three important ways. First, using a flexible difference-in-difference approach we can uncover novel evidence on the dynamics of bank's adjustments to increased capital requirements. For example, we are able to identify a short-lived effect on equity which is not evident when considering the full post-reform period. Second, having established that a reduction in risk-weighted assets is an important margin of adjustment for banks, we dig deeper into *how* banks reduce risk-weighted assets. We focus on how banks decrease corporate lending *relative* to household lending, as a way of reducing the average risk weight on their portfolio. We show that the shift from corporate lending to household lending can explain roughly 80 percent of the observed decline in average risk weights.[4]

Third, and most importantly, we document that the increase in capital ratios has negative spillover effects to employment using data on a much wider set of firms than what is typically used in the literature.[5] Most of the existing literature, such as Gropp, Mosk, Ongena, and Wix (2018), uses data on syndicated loans, a debt market typically skewed towards bigger and less bank-dependent firms. Evaluating the real effects of capital requirements is therefore challenging, as outcomes are only evaluated for a subset of the firms in the economy. Using data on all limited liability firms, we find that the aggregate real effects of capital requirements are substantially understated if smaller firms are not considered. In fact, our employment results relate to a larger literature on credit shocks in general. Early seminal papers on this topic include Bernanke, Lown, and Friedman (1991) and Peek and Rosengren (1996). Recent contributions are for instance Chodorow-Reich (2014) and Greenstone, Mas, and Nguyen (2014), who document that bank credit was important for employment growth during the Great Recession. Greenstone, Mas, and Nguyen (2014) also look for employment effects during normal economic times, without finding any. Our results suggest that the importance of bank credit is *not* limited to episodes of economic turmoil.

Our empirical results show that banks rebalance their portfolio when capital requirements increase. We tie our findings to the optimal design of capital regulation, specifically the design of risk weights and countercyclical capital requirements. The theoretical literature on bank regulation is

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[3]While Gropp, Mosk, Ongena, and Wix (2018) do not find any effect on average risk weights, their result still indicates portfolio rebalancing when comparing corporate and retail lending. However, their results are not directly comparable to ours, as they do not separate between household lending and lending to SMEs.

[4]Note that because risk weights vary across several dimensions, it is possible that credit is redirected from the corporate sector to the household sector, even if there is no effect on average risk weights. Directly studying the impact on firm and household credit is therefore crucial in uncovering potential portfolio rebalancing.

[5]A notable exception is Jimenez, Ongena, Peydro, and Saurina (2017). However, they (1) do not focus on the portfolio rebalancing aspect of capital requirements and (2) find that, in normal times, there is no adverse effect on firm employment of reductions in credit supply.

nicely summarized in Santos (2001) and Van Hoose (2007). In the spirit of Kim and Santomero
(1988), we construct a simple model showing that capital requirements have no effect on the portfolio
allocation of banks if risk weights are proportional to excess returns, which again are proportional to
systematic risk. Our finding that banks reduce their average risk weights when capital requirements
increase, indicates that assets with relatively low risk weights (such as mortgages) are in fact being
assigned risk weights which are *too low* relative to their systematic risk.[6] An adaptive risk-weighting
scheme, as suggested by Glasserman and Kang (2014), would hence imply adjusting the assigned
risk weights to reduce the difference in risk weights between mortgages and corporate loans.

5.2   Reform and data

5.2.1   Reform

Regulators across the globe use minimum requirements on bank's capital ratios to ensure some level
of loss-absorption capacity. Such requirements are usually risk-weighted, in order to account for
differences in risk-taking across banks. Capital requirements mean that banks need to hold some
amount of equity for every asset they own, or for every loan they grant[7]. Risk-weighting implies
that assets with higher assigned risk weights require banks to hold more equity relative to assets
with lower risk weights. In our sample, the assigned risk weights are mostly exogenous to the bank.
Policy makers determine risk weights for different asset classes, and banks take these as given. The
exception is so called internal ratings based (IRB) banks, which have some freedom in calculating
their own risk weights. The vast majority of banks in our sample are non-IRB banks however, and
our results are robust to excluding IRB-banks from the sample. Hence, we think of the assigned
risk weights as being outside of the banks control and constant over time in the relevant period.

Risk weights vary both across and within asset classes. The most important dimension of
variation for this paper is the difference in risk weights for lending to households relative to firms.
The average risk weight on mortgages for non-IRB banks is 0.35, compared to an average risk weight
on corporate loans of around 1.0 (Andersen 2013, Andersen and Winje 2017). Hence, extending a
corporate loan requires the bank to hold roughly three times as much additional equity as when
extending a mortgage loan.

A bank's risk-weighted capital ratio is given by equation (5.1). Equity is denoted by E, assets by
A and risk weights by α. We use the terms *capital ratio* and *CET1-ratio* interchangeably, although
they rely on slightly different definitions of capital. While capital ratios are based on equity plus
hybrid capital, CET1-ratios are based on so called Tier 1 Core Equity (CET1).[8]

$$\text{Capital Ratio} = \frac{E}{\sum_i \alpha_i A_i} \tag{5.1}$$

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[6] It is possible that a social planner would in fact want to distort bank's portfolio allocations, although this has not
been part of the policy discussion surrounding the design of risk-weighted capital requirements.

[7] We use the popular term "holding equity", although this expression is somewhat misleading. Equity is not an
asset, and as such not something that banks hold, but rather a source of financing.

[8] CET1 capital consists of equity less regulatory deductions (Norges Bank 2014).

Following the financial crisis of 2007/2008, the Basel III accord was put forward by the Basel Committee on Banking Supervision (BCBS 2010). The accord outlined a set of standards on capital and liquidity regulation. One of the prominent features of the Basel III accord was to increase the lower bound on bank's capital ratios. Legislative changes based on the Basel III accord were adopted by the EU in June 2013, in the form of the Capital Requirements Directive IV (CRD IV) and the Capital Requirements Regulation (CRR).

As a member of the European Economic Area, Norway implemented the directive into its own legislation. However, because Norway is not a member of the EU, Norwegian policy makers did not participate in designing the reform. Hence, the new requirements were not tailored to the specifics of the Norwegian bank sector in any way. A challenge with isolating the effects of increased capital requirements is that CRD IV/CRR was accompanied by new liquidity requirements. For Norwegian banks however, satisfying the proposed liquidity coverage ratio (LCR) and the net stable funding ratio (NSFR) was challenging due to a lack of assets satisfying the requirements for high-quality liquid assets (HQLA). For this reason, the implementation of the new liquidity regulation was postponed, and Norwegian authorities "accorded priority to early phase-in of the new capital requirements (Ministry of Finance, 2014).[9] We therefore believe that an advantage of investigating Norwegian bank's adaption to higher capital requirements is that we to a larger extent can isolate the effects of increased capital requirements.

The increase in capital requirements for Norwegian banks was proposed on March 22nd 2013 and adopted on the 1st of July 2013. The new requirements were phased in over a two-year period. As in the EU-legislation, CET1-capital was required to account for ten percent of risk-weighted assets. This included a minimum requirement of roughly five percent, as well as a constant buffer requirement levied on all banks. In addition, a countercyclical capital buffer was adopted. The buffer requirement can vary between 0 and 2.5 percent. All requirements came into effect on the 1st of July 2013 and were phased in incrementally. As a result, Norwegian banks faced a maximum requirement of 12.5 percent. In addition, there was an additional requirement for three systemically important banks.[10] All the requirements, along with the aggregate capital ratio, are illustrated in Figure 5.2.[11][12]

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[9]A revised version of HQLA was introduced later, and the LCR is expected to be fully phased-in by 2018. With respect to the net stable funding ratio (NSFR), the Ministry plans to introduce it in 2018 (Ministry of Finance, 2016). Uncertainty surrounding the definition of HQLA lead the Norwegian authorities to postpone details on how the NSFR would be implemented in Norway. Hence, there is virtually no overlap between our sample period - which ends in 2015 - and the implementation of the new liquidity/funding requirements.

[10]On top of the general requirements, three banks (or credit institutions) were declared systemically important and subjected to an additional requirement of two percent. We only have one systemically important bank in our sample, and all our results are robust to dropping this bank. The two other systemically important institutions are not in our sample because they are not part of The Norwegian Banks Guarantee Fund. One is a Norwegian subsidiary of a Swedish bank (Nordea). The other is a public credit institution which extends loans to municipalities (Kommunalbanken).

[11]The reform of 2013 contained two types of requirements - minimum requirements and buffer requirements. Minimum requirements have to be strictly satisfied at all times. Buffer requirements can in theory be temporarily violated. If a bank's capital ratio falls below a buffer requirement, it is required to take immediate steps to get above the buffer requirement. For example, its dividend policies will be subject to strict regulation. In practice however, banks do not seem to distinguish between buffer and minimum requirements.

[12]The countercyclical capital buffer was set to 1 percent in 2015 and 1.5 percent in 2016.
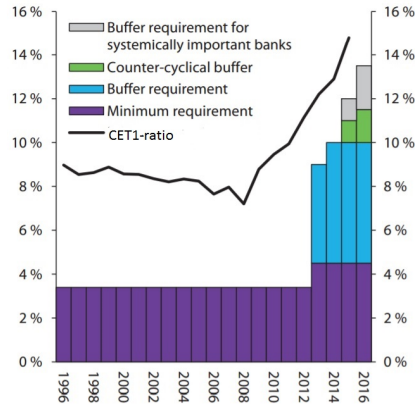
Figure 5.2: Risk-weighted capital requirements for Norwegian banks. Source: Ministry of Finance.

Figure 5.2 documents a steady increase in capital ratios starting shortly after the financial crisis. Such increases are seen also in other European countries. This increase is probably due, at least in part, to an expectation of stricter regulation. However, as documented in the next section, high-capitalized and low-capitalized banks had similar growth rates in capital ratios prior to the reform. Only after the reform do low-capitalized banks significantly increase their capitalization levels *relative* to that of high-capitalized banks.[13]

5.2.2   Data

In our analysis on how banks respond to increased capital requirements, we use quarterly bank balance sheet data. The data is provided by The Norwegian Banks' Guarantee Fund, and contains information on nearly all Norwegian banks and subsidiaries. Foreign banks operating in Norway are not included in the dataset. These banks were also not affected by the Norwegian regulation. Foreign financial institutions account for 15 percent of total assets for banks operating in Norway. The second largest bank in Norway is the Norwegian subsidiary of the Swedish bank Nordea, which is not in our sample.[14] Nordea accounts for roughly 13 percent of the remaining bank assets. Hence, our data covers 74 percent of total bank assets in Norway, and includes 110-120 different banks - depending on the data source. We remove cases with missing observations, and a limited number of observations in which the capital ratio is reported to be zero although risk-weighted assets and equity are both positive and finite.

Our unit of observation in the bank-level analysis is the change in a given variable from quarter i in year $t-1$, to quarter i in year t. The reform was implemented in July 2013, but was proposed in

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[13]Bankers and policy makers have indicated that although Norwegian banks were anticipating increased requirements, the actual increase adopted in 2013 was larger than expected.

[14]After the reform, Nordea Norway changed its status from a subsidiary to a branch, thereby avoiding the new Norwegian capital requirements.

March. We use 2013-Q3 as our reform quarter, but it is possible that banks started reacting already in 2013-Q1. Additionally, some bank responses are likely to appear at the start of the following year. The reason is that some decisions, such as dividend policies, are generally taken once a year at the general assembly, and apply to one calendar year at the time. In our main analysis we use type and quarter interactions, which allows us to be agnostic about when the reform came into effect. In terms of notation, we denote the approximate percentage change in variable X from quarter i in year $t-1$ to quarter i in year t as $\Delta log(X_{it})$.

The average (median) capital ratio prior to the reform was 16.2 (15.9) percent. The distribution is depicted by the solid blue line in Figure 5.3. Roughly 1/4 of the banks in our sample had capital ratios below the new (maximum) requirement of 12.5 percent. The figure shows that banks responded to the reform as expected. A year later the average (median) capital ratio had increased to 16.6 (15.5) percent, and then to 17.1 (16.2) percent after two years. At the same time, the minimum observed capital ratio in our sample increased from 9.7 percent, to 10.7 percent, and finally to the new minimum required level of 11.5 percent. Also note that the right tail of the distribution remains relatively unchanged, reflecting that the high-capitalized banks are not changing their capital ratios in response to the reform.
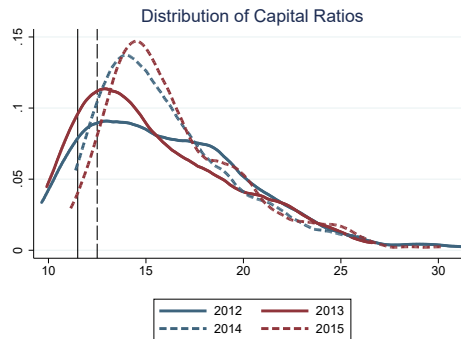
Figure 5.3: Distribution of capital ratios (%) prior to the reform (2012-Q4), 1 year later (2013-Q3), 2 years later (2014-Q3) and 3 years later (2015-Q3). The solid line marks the baseline requirement of 11.5 %, while the dashed line marks the new maximum requirement of 12.5 %.

Summary statistics for 2012-Q4 are reported in Table 5.1. The average bank has assets worth roughly 3,000 million US dollars, while the largest bank has more than 200,000 million US dollars in assets. As reported in the third row, loans make up on average 80 percent of total bank assets. There is substantial variation in bank financing, as captured by deposits as a share of total assets. On average, deposits account for 68 percent of assets. Average risk weights range from 0.45 to 0.99, with a mean of 0.59. These differences reflect, at least in part, differences in lending shares to households and firms. The average bank lends almost five times as much to households relative to firms, but the standard deviation is large. Several banks lend more to firms than to households. As

seen from the two last rows of Table 5.1, most banks in our sample are non-IRB, savings banks. At the end of 2013, the total assets of Norwegian savings banks constituted approximately 91 percent of total assets. The distinction between commercial and savings banks in Norway is not very clear, however. For instance, DNB ASA, the largest bank in Norway and one of the larger banks in Northern Europe, is legally defined as a savings bank but is – in terms of operations – very similar to traditional commercial banks. Larger Norwegian savings banks issue equity, covered bonds and other forms of financing, pay dividends and compete nationally alongside commercial banks.

Variable	Mean	Median	Std.dev.	Min.	Max.	Obs.
Capital Ratio (%)	16.2	15.9	4.2	9.7	31.3	119
Assets (mill USD)	2,913	375	18,422	57	200,345	119
$\frac{\text{Loans}}{\text{Assets}}$	0.80	0.84	0.10	0.20	0.91	119
$\frac{\text{Deposits}}{\text{Assets}}$	0.68	0.67	0.12	0.005	0.89	119
Avg. Risk Weight	0.59	0.58	0.082	0.45	0.99	119
$\frac{\text{Profits}}{\text{Assets}}$ (%)	0.45	0.44	0.21	-0.25	1.64	119
$\frac{\text{Profits}}{\text{Equity}}$ (%)	5.0	4.7	2.8	-3.8	22	119
$\frac{\text{HH-Lending}}{\text{Firm-Lending}}$	4.9	2.5	17.5	0.12	179	114
Savings Bank (binary)	0.87	1	0.33	0	1	119
Non-IRB Bank (binary)	0.94	1	0.24	0	1	119

Table 5.1: Summary statistics for 2012-Q4. NOK/USD = 8.61 (5/8/2017)

Most of our analysis will rely on dividing banks into two groups based on their pre-reform capitalization levels. It will therefore be useful to study the differences between low-capitalized and high-capitalized banks. In the first column of Table 5.2 we report the difference in means between low capitalized and high capitalized banks. Low (high) capitalized banks are defined as banks with pre-reform (2012-Q4) capital ratios below (above) the median. As seen from the first row, on average high-capitalized banks have almost seven percentage points higher capital ratios than low-capitalized banks. They are also smaller, have higher loan-to-asset ratios, and rely more heavily on deposit financing. Further, high-capitalized banks have lower average risk weights and lower profit-to-equity ratios. In addition, high-capitalized banks are more likely to be savings banks and less likely to be IRB-banks. Hence, we conclude that low-capitalized and high-capitalized banks differ along several observable dimensions.

In some of our analysis we exclude the 25 percent most and least capitalized banks. This leaves us with a more homogeneous group of banks, in which we compare quartile 2 banks to quartile 3 banks. The second column of Table 5.2 compares high-capitalized and low-capitalized banks for this restricted sample. The difference in capital ratios is roughly half of the difference for the full sample, but remains statistically significant at the one percent level. All of the other differences between bank types fall substantially, and only the level of deposit financing remains significantly different. Hence, the only statistically significant difference when using the restricted sample is that quartile 3 banks rely more heavily on deposit financing than quartile 2 banks. We document that our results are robust to controlling for all of the variables listed in Table 5.1.

	$mean^{50-100} - mean^{0-50}$	$mean^{50-75} - mean^{25-50}$
Capital Ratio (%)	6.78***	3.19***
Assets (mill USD)	- 4,870*	- 429
$\frac{\text{Loans}}{\text{Assets}}$	0.046**	0.023
$\frac{\text{Deposits}}{\text{Assets}}$	0.10***	0.052**
Avg. Risk Weight	- 0.034**	0.013
$\frac{\text{Profits}}{\text{Assets}}$ (%)	0.011	0.032
$\frac{\text{Profits}}{\text{Equity}}$ (%)	- 1.7***	- 0.81
$\frac{\text{HH-Lending}}{\text{Firm-Lending}}$ +	- 1.21	2.08
Savings Bank (binary)	0.15**	0.071
Non-IRB Bank (binary)	0.083*	0.001
Observations	119 ($^{+}$114)	59 ($^{+}$54)

Table 5.2: Comparison of banks by capitalization level (2012-Q4). Banks are labeled low-capitalized or high-capitalized based on their pre-reform (2012-Q4) ratio. The first column compares banks in quartiles 3 and 4 (high-capitalized) to banks in quartiles 1 and 2 (low-capitalized). The second column compares banks in quartile 3 (high-capitalized) to banks in quartile 2 (low-capitalized).

After documenting how banks adjust their balance sheets in response to increased capital requirements, we proceed by using a loan level dataset provided by The Norwegian Tax Authorities. This dataset contains annual, matched firm-bank data for the universe of Norwegian firms. The tax data has three advantages. First, it lets us observe the entire portfolio of domestic corporate credit for all Norwegian banks, enabling us to do a more granular analysis of how banks respond. Second, it strengthens identification by allowing us to include firm fixed effects to hold demand factors fixed. Firm fixed effects are only feasible for multiple-bank firms however. In our test for correlated supply and demand shocks we therefore rely on the roughly 10 percent of firms which borrow from multiple banks. Using the tax data, we can observe the interest paid on loans. This enables us to also study the price effects of the reform. Finally, the loan level data lets us trace out the effect of bank credit contractions on the real economy by linking firms and banks. For the latter exercise we also rely on a final dataset containing firm level employment data. This data comes from the firms' annual reporting, compiled in a national public register (*The Bronnoysund Register*).

5.3 Bank Level Analysis

We start by investigating how banks respond to increased capital requirements. Recall that a bank's risk-weighted capital ratio in period t is given by

$$\text{Capital Ratio}_t = \frac{E_t}{\sum_i \alpha_{ti} A_{ti}} = \frac{E_t}{\overline{\alpha_t}\, A_t}$$

where the average risk weight is given by $\overline{\alpha} \equiv \frac{\sum_i \alpha_i A_i}{\sum_i A_i}$ and total assets by $A \equiv \sum_i A_i$. Taking logs and first differences yields

$$\Delta \log \left(Capital\ Ratio_t \right) = \Delta \log \left(E_t \right) - \Delta \log \left(A_t \right) - \Delta \log \left(\overline{\alpha}_t \right) \tag{5.2}$$

As seen from equation (5.2), banks can increase their capital ratio growth rate in three ways. First, they can increase the growth in equity, for example through retained earnings. Second, they can reduce the growth in assets, which is likely to imply a reduction in credit supply. Finally, they can reduce the growth in the average risk weight $\bar{\alpha}$. This implies shifting their asset composition towards assets with lower assigned risk weights. In this section we decompose the reform-induced change in capital ratio growth rates, and quantify the relative importance of equity, assets and average risk weights.

5.3.1   Methodology

Our analysis relies on the cross-sectional differences in capital ratios prior to the reform. Whereas high-capitalized banks were not directly affected by the reform, low-capitalized banks had to increase their capitalization levels. The main identification challenge is to separate supply factors from demand factors. If high-capitalized and low-capitalized banks lend to systematically different clients, we risk falsely attributing demand-driven changes in bank outcomes to higher capital requirements. For example, low-capitalized banks may be lending to firms with low credit demand, which could reduce equilibrium lending regardless of the reform. We address this important issue in three ways. First, we use a flexible difference in difference methodology to directly test the standard assumption of parallel trends for the high-capitalized and low-capitalized banks. Hence, we can explicitly test whether low-capitalized and high-capitalized banks have similar outcomes prior to the reform, suggesting that they are not lending to systematically different clients. Later, in Section 5.5 we use loan level data and follow Khwaja and Mian (2008) in including firm fixed effects. In this case, the effect of bank capitalization on credit supply is identified while holding firm characteristics fixed. Finally, in Section 6, we back out bank specific interest rates using loan level tax data. This allows us to evaluate not only how lending *volumes* are affected by higher requirements, but also how lending *prices* are affected. While a negative supply shock has the same qualitative implications for lending volumes as a negative demand shock, the two shocks have different implications for prices. Hence, an increase in interest rates supports the interpretation of the fall in credit being supply-driven.

The flexible difference in difference regression is specified in equation (5.3). Our main dependent variables are the growth rates in capital ratios, equity, assets and average risk weights for bank i. Hence, we estimate equation (5.3), with $Y_{i,t} = \{$Capital Ratio$_{i,t}$, Equity$_{i,t}$, Assets$_{i,t}$, Risk Weight$_{i,t}\}$. The time fixed effects δ_t account for common cyclical patterns in these variables. We use a type dummy $D_i = 0$ if bank i is high-capitalized ("low treatment intensity"), and $D_i = 1$ if bank i is low-capitalized ("high treatment intensity"). The coefficients of interest are the $\gamma_{1,t}^D$'s on the type×time interaction terms. These coefficient estimates identify the difference in $\Delta log(Y_{i,t})$ for high and low-capitalized banks in a given year, relative to the average difference between the two bank types. We can directly test the parallel trends assumption prior to the reform by testing whether $\gamma_{1,t}^D = 0\ \forall\ t < 0$, using $t = 0$ to capture the time of the reform. If there are anticipation effects of the reform,

this will show up in our estimates as a violation of the parallel trends assumption. Given that the parallel trends assumption holds, the treatment effects will be captured by the $\gamma_{1,t}^D$'s for $t \geq 0$. Note that we will also be able to test the hypothesis of constant treatment effects, i.e. $\gamma_{1,t}^D = \bar{\gamma}^D \ \forall \, t \geq 0$. This will turn out not to hold, as the effect of the reform appears to be transitory. Once banks have adjusted to the new capital requirements, low-capitalized and high-capitalized banks return to their previous parallel trends. Hence, a comparison of the $\gamma_{1,t}^D$'s for different post-reform time periods will allow us to map out the dynamic treatment effects.

$$\Delta log(Y_{i,t}) = \alpha + \sum_k \delta_k \mathbf{1}_{t=k} + \gamma_i^D D_i + \sum_t \gamma_{1,k}^D D_i \times \mathbf{1}_{t=k} + \epsilon_{i,t} \tag{5.3}$$

The flexible difference in difference specification is attractive because it can explicitly test the parallel trends assumption, and because it allows for dynamic treatment effects. However, it is quite data demanding, and will sometimes fail to produce significant results in cases where more restrictive difference in difference estimations *will* produce significant results (Reggio and Mora Villarrubia 2012). Therefore, after having verified the validity of the parallel trends assumptions, we proceed by estimating a less data demanding regression, as specified in equation (5.4). Instead of interacting type with time dummies, we now interact type with a dummy for the full post-reform period. That is, $I_t^{post} = 0$ if $t < 0$, and $I_t^{post} = 1$ otherwise. This specification imposes a parallel trends assumption explicitly, which we are comfortable doing based on the results from the flexible difference in difference regression. The specification also imposes a constant treatment effect. Hence, the coefficient estimate $\hat{\beta}$ should be interpreted as the average treatment effect in the post-reform period.

$$\Delta log(Y_{i,t}) = \alpha + \sum_k \delta_k \mathbf{1}_{t=k} + \gamma_i^D D_i + \beta D_i \times I_t^{post} + \epsilon_{i,t} \tag{5.4}$$

The baseline estimates are based on regressions without control variables. This is a valid approach if our identifying assumption holds. That is, pre-reform capitalization levels are only related to post-reform outcome variables through the effect on changes in capital ratios. We also report results controlling for numerous variables such as size, average risk weight, asset composition, deposit financing, return on equity and organizational structure. Our results are largely unchanged. Finally, standard errors are clustered at the bank level.[15]

5.3.2   Results

The upper, left panel of Figure 5.4 plots the growth rate in capital ratios for low-capitalized and high-capitalized banks. In the time prior to the reform, low-capitalized and high-capitalized banks have similar changes in capital ratios. These pre-reform growth rates fluctuate around zero, indicating that capital ratios are roughly constant. At the time of the reform, a new pattern emerges. While high-capitalized banks continue to have growth rates close to zero, there is a spike in growth rates

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[15]Clustering at other levels provide less conservative standard errors.

for low-capitalized banks. This divergence seems to start when the reform is announced, and grows in magnitude over time. By the end of the sample the difference decreases, suggesting that the transitory adjustment in capital ratios is coming to an end.

Using $\Delta log(Cap.Ratio_{i,t})$ as our dependent variable, the flexible difference in difference regression in equation (5.3) results in the interaction coefficients plotted in the upper, right panel of Figure 5.4.[16] The interaction terms prior to the reform are stable and not significantly different from zero, implying that the parallel trends assumption holds. Then, at the time of the reform, the interaction terms start increasing in magnitude and statistical significance. Low-capitalized banks have higher annual growth in capital ratios than high-capitalized banks for six consecutive quarters. The difference is no longer statistically significant for the last observation in our sample, suggesting that the adjustment in capital ratios is limited to a slightly less than two-year period.

A potential concern is that the divergence in capital ratio growth rates is partly driven by mean reversion. If banks target similar capital ratios, low capitalized banks may have high growth rates in capital ratios for reasons unrelated to the reform. To test whether mean reversion can explain the observed patterns we perform a placebo test in which we repeat our analysis one year prior to the reform. That is, we define banks as low or high capitalized based on their capital ratios in 2011, and test whether the two groups have different growth rates in capital ratios after 2012-Q3. As illustrated in Figure D.1 in Appendix D.1, there is no divergence at this artificial reform date. Instead, there is a (noisy) divergence at the time of the reform, suggesting that the reform itself is the driving force behind our results.

How much of the increase in capital ratios is due to an increase in equity? We plot the equity results in the second row of Figure 5.4. The left panel depicts growth rates in equity for low-capitalized and high-capitalized banks. Low-capitalized banks have consistently higher growth rates in equity prior to the reform, but the difference between the two bank types is stable. There is no apparent trend break at the time of the reform. However, an interesting pattern emerges starting as of 2014-Q1. Both bank types increase the growth in equity, but the increase is larger for low-capitalized banks. We believe this delayed response to the reform is due to banks decision making processes. Important decisions such as dividend policies are taken at the general assembly, and apply to one calendar year at the time. The data is consistent with low-capitalized banks deciding to lower their dividend payouts for the calendar year 2014, contributing to higher equity growth through retained earnings.

In the right panel we plot the interaction term coefficients from equation (5.3) with $Y_{i,t} = $ Equity$_{i,t}$. Prior to the reform, the interaction coefficients are stable and not significantly different from zero. Consistent with the raw data, there is no statistically significant effect at the time of the reform. However, low-capitalized banks do have significantly higher growth in equity from 2013 to 2014, suggesting that part of the increase in capital ratios is due to an increase in equity. This

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[16]Capital ratios are defined as bank's CET1-ratios. Because CET1-ratios have only been reported as of 2012, we use regular capital ratios as a proxy for CET1-ratios prior to 2012. Note that this leaves us with at least two pre-reform CET1 observations, meaning that the break in CET-ratios at the time of the reform cannot be explained by measurement issues.

effect is however limited to a one calendar-year period, and relatively modest in size.

We next move on to consider the impact on assets in the third row of Figure 5.4. The growth in assets for low-capitalized and high-capitalized banks are plotted in the left panel. Although the data is somewhat noisy, the two bank types have similar growth rates in assets prior to the reform. At the time of the reform however, there is a decline in asset growth for low-capitalized banks. High-capitalized bank on the other hand, increase their growth rates.
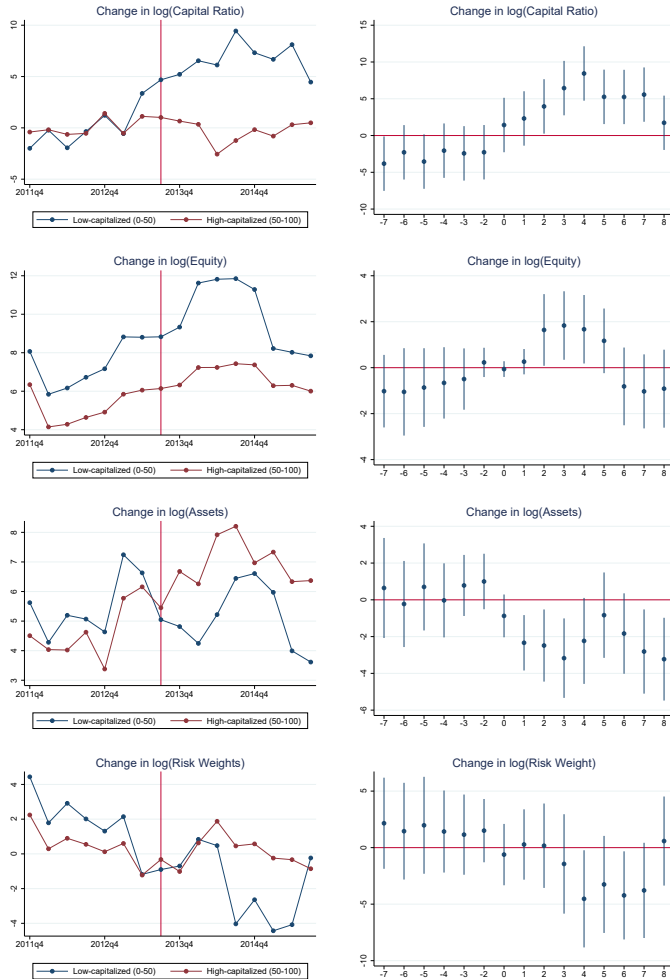
Figure 5.4: Capital Ratio, Equity, Assets and Average Risk Weights. Banks are divided into groups based on their 2012 capital ratio. Left panels: Growth rates in capital ratios, equity, assets and average risk weights for low-capitalized (below median) and high-capitalized (above median) banks. The growth rate for $year_t$-$quarter_i$ denotes the (approximate) percentage change from $year_{t-1}$-$quarter_i$ to $year_t$-$quarter_i$. The solid red line marks the growth rate from 2012-Q3 to 2013-Q3 (the reform date). Right panels: Regression results from estimating equation (5.3) with dependent variable $Y_{i,t} = \{$Capital Ratio$_{i,t}$, Equity$_{i,t}$, Assets$_{i,t}$, Risk Weight$_{i,t}\}$. Interaction coefficients $\gamma_{1,t}^D$ are plotted relative to time $t = -1$. Standard errors are clustered at the bank level. Time zero marks the growth rate from 2012-Q3 to 2013-Q3 (the reform date).

The right panel depicts interaction coefficients from the flexible difference in difference regression in equation (5.3), with growth in assets as the dependent variable. Prior to the reform, the

interaction coefficients are small and stable. The parallel trend assumption thus appears reasonable. Starting at the reform date, low-capitalized banks experience lower growth in assets than high-capitalized banks. This effect seems to persist for the full post-reform period, although there is one date for which the difference is not statistically different from zero. Hence, it appears that a reduction in asset growth contributed substantially to the increase in capitalization levels caused by the reform.

Finally, we study the effect on average risk weights, and plot the results in the bottom row of Figure 5.4. High-capitalized banks have slightly lower growth in average risk weights *prior* to reform, but higher growth in average risk weights *after* the reform, as illustrated in the left panel. The data is consistent with a reduction in average risk weights for low-capitalized banks following the reform. As was the case with equity, the difference between low-capitalized and high-capitalized banks increases with the beginning of a new calendar year.

As before, we plot interaction coefficients from regressing equation (5.3) with $Y_{i,t} = \text{Risk Weight}_{i,t}$ as the dependent variable in the right panel. The interaction coefficients are stable and not statistically different from zero prior to the reform. There is a small trend break at the time of the reform, but this is not statistically significant. However, as seen from the raw data, there appears to be a delayed effect starting at the beginning of the new calendar year in 2014-Q1. Low-capitalized banks significantly reduce their average risk weights relative to high-capitalized banks. The effect is large in magnitude, but not as precisely measured as the reduction in asset growth. Still, low-capitalized banks seem to have relied substantially on a reduction in the average riskiness of their portfolios to achieve the observed increase in risk-weighted capital ratios.

The flexible difference in difference regressions have confirmed that the parallel trends assumption seems to hold for all our outcome variables. Hence, we are comfortable estimating the more restrictive difference in difference regression in equation (5.4). Note that this specification imposes a constant treatment effect, so the estimates should be interpreted as average treatment effects over the time period studied.

In Table 5.3 we report regression results for the four outcome variables studied above. The first column shows results using $\Delta log(\text{Capital Ratio}_{i,t})$ as our dependent variable. In the post-reform period, low-capitalized banks had on average 6.8 percentage points higher growth in capital ratios than high-capitalized banks. The difference is significant at the one percent level of significance.

Results using the growth in equity as the dependent variable are reported in the second column. In the post-reform period, low-capitalized banks had on average 1.0 percentage points higher growth in equity than high-capitalized banks. This difference is however not statistically significant. The reason is that the equity response seems limited to a one-calendar-year period, resulting in a low average treatment effect. Hence, we conclude that although there does appear to have been some response through equity, changes in equity growth are not quantitatively as important as changes in risk-weighted assets in explaining the increase in capital ratios.

Column three reports results using the growth in assets as the dependent variable. In the post-reform period, low-capitalized banks had on average 2.6 percentage points lower growth in assets

than high-capitalized banks. The difference is significant at the five percent level of significance. Finally, column four reports results using the growth in average risk weights as the dependent variable. We estimate that low-capitalized banks had on average 3.3 percentage points lower growth in average risk weights than high-capitalized banks, in the post-reform period. This difference is significant at the one percent level of significance.

The results are robust to adding control variables, as reported in the lower panel of Table 5.3.[17] While none of the point estimates are significantly different from the estimation without control variables, the impact on equity is slightly larger and significant at the ten percent level.

	(1)	(2)	(3)	(4)
	$\Delta log(Cap.Ratio_{i,t})$	$\Delta log(Equity_{i,t})$	$\Delta log(Assets_{i,t})$	$\Delta log(RiskWeight_{i,t})$
$D_i \times I_t^{post}$	6.830***	0.966	-2.613**	-3.252***
	(5.44)	(1.43)	(-2.63)	(-2.77)
Time FE	yes	yes	yes	yes
Type FE	yes	yes	yes	yes
Controls	no	no	no	no
Clusters	120	120	120	120
Observations	1,907	1,907	1,907	1,907
$D_i \times I_t^{post}$	6.387***	1.223*	-2.511**	-2.653**
	(4.89)	(1.79)	(-2.46)	(-2.32)
Time FE	yes	yes	yes	yes
Type FE	yes	yes	yes	yes
Controls	yes	yes	yes	yes
Clusters	114	114	114	114
Observations	1,824	1,824	1,824	1,824

t statistics in parentheses, Std. err. clustered at bank level

* $p < .10$, ** $p < .05$, *** $p < .01$

Table 5.3: Restrictive difference-in-differences estimation. Regression results from estimating equation (5.4).

In order to decompose the growth rate in capital ratios we simply divide the coefficients in columns 2, 3 and 4 with the coefficient in column 1.[18] A one percentage point higher reform-induced growth rate in capital ratios leads to an increase in equity growth of 0.14 percentage points, a decrease in asset growth of 0.38 percentage points, and a decrease in the growth rate of average risk weights of 0.48 percentage points. We thus conclude that more than 85 percent of the increase in capital ratios is achieved by adjusting risk-weighted assets. Of these 85 percent, the majority is explained by a portfolio rebalancing effect, in which banks substitute high-risk assets with low-risk assets.[19] In the next section, we further explore why this is the case.

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[17]Control variables include pre-reform values for assets, loan-to-assets, deposit-to-assets, average risk weights, profit-to-equity, household lending relative to firm lending, saving bank status and IRB bank status.

[18]Identical results can be obtained by a two staged least square regression, with the predicted change in capital ratio as the independent variable.

[19]In a previous version of the paper, we employed a continuous treatment intensity variable rather than grouping banks according to high and low treatment intensity. While this approach uses more of the cross-sectional variation available in the data, it does not fully exploit the time variation. We prefer the flexible difference in difference analysis,

5.4   Portfolio Rebalancing

5.4.1   Why do banks rebalance their portfolio?

The reduction in average risk weights is due to a shift in portfolio composition. In this section we analyze this in more detail. To fix ideas, we start by setting up a simple model based on Freixas and Rochet (2008).

The model is static. A bank allocates funds to different competitive lending markets. For simplicity, we assume that equity E is fixed. Although this is a strict assumption, our empirical results from the previous section suggest that the impact on equity is limited. In addition to equity, the bank finances its loan portfolio by raising deposits D. We assume that A_0 is a risk-free asset, i.e. government bonds or central bank reserves, and that assets $1, ..., n$ are loans to different markets. The bank chooses a vector of asset allocations $\boldsymbol{A} = \{A_1, ... A_n\}$ in n lending markets. For instance, we can think about A_1 as being single-family mortgages, A_2 as being corporate loans to $BB+$ rated public corporations etc. The remainder of the banks funds is used to purchase the riskless asset.

The vector of expected excess returns in the respective lending markets is joint-normal with mean $\rho = \{\rho_1, ...\rho_n\}$, and with invertible variance-covariance matrix Σ. The bank is subject to a capital requirement $\bar{k}$. By law, the bank is required to ensure that

$$\frac{E}{\alpha \cdot \boldsymbol{A}} \geq \bar{k} \tag{5.5}$$

where $\cdot$ denotes the dot-product and $\alpha = \{\alpha_1, ..., \alpha_n\}$ denotes a vector of pre-assigned risk-weights corresponding to the respective loan categories.[20]

We assume that the bank (or bank owner) has CARA preferences. This, in combination with the normality of the asset-returns, allows us to write the certainty equivalent of the bank-owners pay-off as

$$U(\mathbf{A}) = \rho^T \mathbf{A} - \frac{1}{2}\gamma \mathbf{A}^T \Sigma \mathbf{A} \tag{5.6}$$

where γ is the bank owner's coefficient of risk-aversion. Thus, the portfolio allocation problem is to maximize utility given by equation (5.6), subject to the capital requirement (5.5) and the balance sheet constraint $\sum A = D + E$.

Letting λ denote the shadow-value of the capital requirement constraint, the set of first-order conditions for portfolio allocations can be written compactly as

$$\rho - \gamma \mathbf{A}\boldsymbol{\Sigma} - \lambda\bar{k}\alpha = 0 \tag{5.7}$$

or in terms of portfolio allocations (in dollars invested in each asset)

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as it explicitly allows us to test the parallel trends assumption. However, the qualitative results are reassuringly very robust to using other approaches.

[20]Since the zeroth asset is risk-free, it is assigned a risk-weight of zero percent.

$$\mathbf{A} = \Sigma^{-1} \frac{\rho - \lambda \bar{k} \alpha}{\gamma} \tag{5.8}$$

In the absence of a binding capital requirement ($\lambda = 0$), this is the mean-variance efficient portfolio in the sense of the traditional capital asset pricing model (CAPM).

Equation (5.8) sheds light on how risk-weighted capital requirements affect banks lending decisions. Because the effective excess return is reduced by a binding capital requirement, the banks overall holdings of risky assets fall. How is the provision of credit to various sectors affected? This depends on the pre-assigned risk weights, and how they relate to systematic risk. The traditional CAPM would require that in a competitive market, the return-vector ρ is colinear to the systematic risk of the various assets. From equation (5.8) it is clear that the introduction of a binding risk-weighted capital requirement ($\lambda > 0$) could lead to an inefficient allocation across risky assets, relative to the mean-variance efficient benchmark. This occurs when the risk-weights α are not proportional to ρ, and therefore not proportional to systematic risk.

We illustrate this point with a simple example of two lending markets, i.e. $n = 2$. Maximizing (5.6) with respect to (5.5) and the balance sheet condition, results in the optimal allocations

$$A_1^* = \frac{\rho_1 - \lambda \bar{k} \alpha_1}{\gamma(\sigma_{11}^2 + \sigma_{21}^2)}, \quad A_2^* = \frac{\rho_2 - \lambda \bar{k} \alpha_2}{\gamma(\sigma_{12}^2 + \sigma_{22}^2)}$$

It is easy to show that $\frac{A_1^*}{A_2^*}|_{\lambda>0} = \frac{A_1^*}{A_2^*}|_{\lambda=0}$ if and only if $\frac{\alpha_1}{\alpha_2} = \frac{\rho_1}{\rho_2}$[21]. In words, the relative asset allocation is independent of the capital requirement only if the relative risk weights are proportional to expected returns, and thereby to systematic risk. Suppose however that this was not the case, and that $\frac{\alpha_1}{\alpha_2} < \frac{\rho_1}{\rho_2}$. This implies that the relative risk weight of the first asset, A_1, is too low, causing A_1 to be inefficiently high relative to the efficient portfolio. In other words, the introduction of capital requirements would in this case lead to a shift in lending towards the first market, away from the second market.

5.4.2 How do banks rebalance their portfolio?

Due to the large difference in average risk weights between corporate lending and household lending, the reduction in average risk weights can imply a relative reduction in corporate lending. We now proceed to investigate whether this is indeed the case.

We have quarterly balance sheet data for corporate lending starting in 2012. Growth rates for corporate lending based on the balance sheet data are depicted in the left panel of Figure 5.5. Although we only have two pre-reform observations for growth in firm lending, the picture is quite striking. Low-capitalized and high-capitalized banks have very similar growth rates in corporate lending prior to the reform, if anything low-capitalized banks have slightly higher growth rates.

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[21]The argument also applies when going from a binding constraint to a stricter constraint. To see this consider increasing capital requirements from $\bar{k}$ to $\bar{k}'$, with respective shadow values λ and λ'. The relative asset allocations $\frac{A_1}{A_2}$ and $\frac{A_1'}{A_2'}$ will once again equal each other if $\frac{\alpha_1}{\alpha_2} = \frac{\rho_1}{\rho_2}$. Specifically, $\frac{A_1}{A_2} = \frac{A_1'}{A_2'} \iff (\alpha_1\rho_1 - \alpha_2\rho_2)(\lambda\bar{k} - \lambda'\bar{k}') = 0$. Hence, observing $\frac{A_1}{A_2} \neq \frac{A_1'}{A_2'}$ implies $\frac{\alpha_1}{\alpha_2} \neq \frac{\rho_1}{\rho_2}$.

This changes abruptly at the time of the reform. While high-capitalized banks continue to see growth rates in corporate lending volumes of 4-6 percent, the growth rate in corporate lending for low-capitalized banks plummets. In fact, low-capitalized banks have negative growth in firm lending for four consecutive observations. Mirroring the evolution in capital ratios and average risk weights, the difference in lending growth is mostly over by the end of our sample. The right panel of Figure 5.5 plots the interaction coefficients from estimating equation (5.3) using the growth in firm lending as the dependent variable. The interaction coefficients are small and insignificant prior to the reform, and then become negative and significantly different from zero after the reform. Hence, we conclude that low-capitalized banks significantly and substantially reduced corporate lending growth in response to the reform.
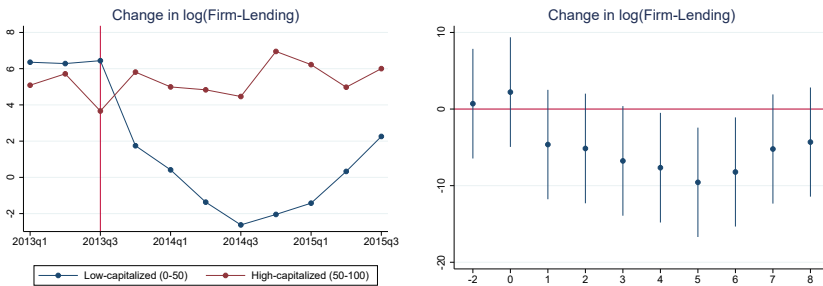
Figure 5.5: Firm-lending. Banks are divided into groups based on their 2012 capital ratio. Left panel: Growth rates in capital ratios for low-capitalized (below median) and high-capitalized (above median) banks. The growth rate for $year_t$-$quarter_i$ denotes the (approximate) percentage change from $year_{t-1}$-$quarter_i$ to $year_t$-$quarter_i$. The solid red line marks the growth rate from 2012-Q3 to 2013-Q3 (the reform date). Right panel: Regression results from estimating equation (5.3) with dependent variable $Y_{i,t} = $ Firm-lending$_{i,t}$. Interaction coefficients $\gamma_{1,t}^{D}$ are plotted relative to time $t = -1$. Standard errors are clustered at the bank level. Time zero marks the growth rate from 2012-Q3 to 2013-Q3 (the reform date).

In order to obtain a longer time series for corporate lending, and to confirm our results using an alternative data source, we aggregate the loan level tax data into a time series for corporate bank lending. We then redo the above analysis, now using annual data. The results are depicted in Figure 5.6. First, note that the assumption of parallel trends is not only valid in the short time period prior to the reform shown in Figure 5.5, it seems to hold for at least a six-year period prior to the reform. Lending growth is high for both bank types prior to the financial crisis, before falling substantially in 2009. Credit growth is then fairly stable between five and ten percent for both bank types in the period leading up to the reform. While high-capitalized banks continue to have fairly stable growth rates in firm lending post-reform, the growth rate in firm lending for low-capitalized banks once again plummets. As was the case for the quarterly data, low-capitalized banks even experience negative credit growth in the year following the reform. As before, we report interaction coefficients from regressing equation (5.3), using the annual change in firm lending as our dependent variable. These interaction coefficients are reported in the right panel of Figure 5.6. Prior to the reform,

the interaction coefficients are small and insignificant. Post-reform, the interaction coefficients are negative and significantly different from zero. Hence, the tax data confirms a significant reduction in corporate lending growth for low-capitalized banks following the reform.

Figure 5.6: Firm-lending, tax data. Banks are divided into groups based on their 2012 capital ratio. Left panel: Growth rates in corporate lending for low-capitalized (below median) and high-capitalized (above median) banks. The growth rate for $year_t$ denotes the symmetric percentage change from $year_{t-1}$ to $year_t$. The dashed red line marks the growth rate from 2012 to 2013 (the reform year). Right panel: Regression results from estimating equation (5.3) with dependent variable $Y_{i,t} =$ Firm-lending$_{i,t}$. Interaction coefficients γ_{1t}^D are plotted relative to year 2012. Standard errors are clustered at the bank level.

After having confirmed that the parallel trends assumption is appropriate, we now move on to estimating the more restrictive difference in difference regression specified in equation (5.4). The results are reported in Table 5.4. Using the quarterly balance sheet data, we find that following the reform, low-capitalized banks had on average 5.8 percentage points lower growth in corporate lending than high-capitalized banks. Using the aggregated tax data increases this number to 8.9, as reported in the second column.[22] These effects are substantially larger than the total reduction in assets, suggesting that low-capitalized banks are especially willing to reduce *firm* lending. Scaling the results with the increase in capital ratios, we find that a one percentage point higher increase in capital ratios leads to a 1.0 to 1.5 percentage points lower growth in corporate credit supply.[23]

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[22]Note that the quarterly data on corporate lending from The Norwegian Banks Guarantee Fund is not exactly the same as the annual data on corporate lending from The Norwegian Tax Authorities, as the latter only consists of Norwegian limited liability firms and not foreign firms and sole proprietorships.

[23]This is equivalent to regressing the change in corporate lending on the predicted change in capital ratios.

	(1)	(2)
	Δlog(Firm-Lending$_{it}$)	Δlog(Firm-Lending$_{it}$)
$D_i \times I_t^{post}$	-5.834**	-8.930***
	(-2.55)	(-2.97)
Time FE	yes	yes
Type FE	yes	yes
Data Source	balance sheet	tax data
Clusters	116	110
Observations	1,251	1,094

t statistics in parentheses, Std. err. clustered at bank level
* $p < .10$, ** $p < .05$, *** $p < .01$

Table 5.4: Restrictive difference-in-differences estimation - Corporate credit supply. Regression results from estimating equation (5.4).

What about household lending? In Figure 5.7 we plot the growth rates in household and firm lending, for low-capitalized and high-capitalized banks.[24] Focusing first on the dashed lines, we see that high-capitalized banks have stable and similar growth rates in firm and household lending. Lending growth to both groups fluctuates between four and seven percent, with no apparent trend breaks. Contrast this to the low-capitalized banks as captured by the solid lines, which have a striking divergence in the growth rates of household lending and firm lending post-reform. While lending growth to the household sector remains stable, lending growth to the corporate sector falls to negative values. Hence, we conclude that low-capitalized banks reduce lending growth to the firm sector relative to the household sector, whereas high-capitalized banks do not.
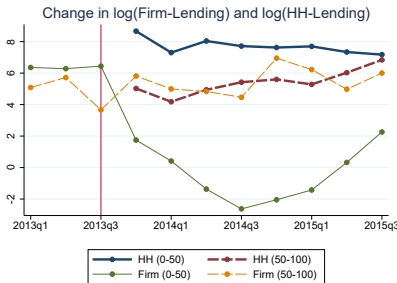
Figure 5.7: Firm-lending and household-lending. Growth rates in firm and household lending for low-capitalized (below median) and high-capitalized (above median) banks. Banks are divided into groups based on their 2012 capital ratio. The growth rate for $year_t$-$quarter_i$ denotes the (approximate) percentage change from $year_{t-1}$-$quarter_i$ to $year_t$-$quarter_i$. The solid red line marks the growth rate from 2012-Q3 to 2013-Q3 (the reform date).

Due to the large differences in risk weights between mortgage lending and corporate lending, cutting back on corporate lending is an efficient way to reduce average risk weights. In Figure 5.8

[24]We only have data on household lending for a shorter time-period, which means that we cannot estimate the same regressions as for firm lending. However, the visual evidence from Figure 5.7 makes us confident that there is no or limited response in mortgage lending.

we plot the change in corporate lending relative to household lending as a function of the change in average risk weights. There is a strong positive relationship between the two variables, suggesting that the reduction in average risk weights reflects a reduction in firm lending relative to household lending. We next explore this correlation with some simple calculations based on the average bank's balance sheet.
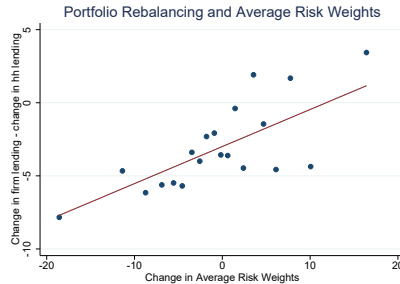
Figure 5.8: Portfolio rebalancing. Binscatter of Δlog(Firm-lending) $- \Delta log$(HH-lending) and Δlog(Risk weight) for all banks. Binscatter groups the x-axis variable into equal-sized bins, computes the mean of the x-axis and y-axis variables within each bin, then creates a scatterplot of these data points.

Can the shift from firm lending to household lending quantitatively explain the reduction in average risk weights? Shifting from corporate lending to household lending will generally reduce the average risk weight on a bank's portfolio. However, the magnitude will depend on the characteristics of the specific firm and household loans. Banks can also reduce their average risk weights through other channels, for example by changing the share of other assets it holds (for example government bonds). Additionally, shifts within asset classes could also reduce average risk weights. For example, by extending low-risk corporate loans the bank could decrease its average risk weight, while holding the total corporate lending share constant.

In order to evaluate the quantitative importance of shifting from firm lending to household lending we perform some back-of-the-envelope calculations using the balance sheet of an average low-capitalized bank. We calculate the *implied* change in risk weights if the only moving part of the balance sheet is the share of household versus firm lending. Comparing this estimate to the *observed* change in risk weights gives us at least a rough idea of whether the relative reduction in corporate lending is quantitatively important.

We observe total assets, household lending and firm lending. We thus define other assets to be the component of assets which is neither household nor firm lending $A^{other} = A^{tot} - L^{HH} - L^{firm}$. The average risk weight ARW is then given by equation (5.9). While we observe the average risk weight, we do not observe the actual risk weights for each asset class. Hence, we assume that $\alpha^{HH} = 0.35$, which is the average risk weight on mortgages for non-IRB banks (Andersen 2013)[25].

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[25]The risk weight of 0.35 is for mortgages which have loan-to-value ratios of maximum 80 percent. As this is the recommended maximum loan-to-value ratio, the majority of mortgages fall within this category.

For corporate lending we assume $\alpha^{firm} = 1.0$, in line with the average risk weight on firm loans for non-IRB banks as outlined in Andersen and Winje (2017)[26]. The risk weight on other assets is then backed out to match the observed average risk weight, resulting in $\alpha^{other} = 0.52$.

$$ARW = \frac{L^{HH}}{A^{tot}}\alpha^{HH} + \frac{L^{firm}}{A^{tot}}\alpha^{firm} + \frac{A^{other}}{A^{tot}}\alpha^{other} \tag{5.9}$$

The change in average risk weights depends on the change in the asset composition between household lending, firm lending and other assets, as well as changes in the respective risk weights. We are interested in isolating the impact of shifts from corporate lending to household lending. To do so we perform a counterfactual exercise in which we assume that the risk weights (α^{HH}, α^{firms}, α^{other}) and the share of other assets $\frac{A^{other}}{A^{tot}}$ is constant over time. The latter assumption necessarily implies that the total share of household and firm lending $\frac{L^{HH}+L^{firm}}{A^{tot}}$ is also constant over time. However, the quantity of household lending relative to firm lending is set to match the data. The first column of Table 5.5 lists the observed average risk weights for low-capitalized banks from 2013 to 2015[27]. Over the period, average risk weights fell by 2.5 percent. Simultaneously, household lending relative to firm lending increased by 17 percent. Note that in the same period high-capitalized banks experienced an *increase* in average risk weights and a *decrease* in household lending relative to firm lending. Keeping risk weights and the share of other assets fixed, we calculate the implied average risk weights in the last column of Table 5.5. By construction, the average risk weight in the first year is the same as in the data. Shutting down the effect of changes in risk weights for the different asset classes and changes in the share of other assets, we calculate a fall in implied risk weights of 2.0 percent. Hence, the increase in household lending relative to firm lending can explain 80 percent of the observed reduction in average risk weights for low-capitalized banks. We thus conclude that considering average balance sheet data, the fall in relative corporate lending is quantitatively consistent with the reduction in average risk weights. Moreover, although these back-of-the-envelope calculations are quite rough, they suggest that shifts from firm lending to household lending can potentially account for nearly all of the reduction in average risk weights.

	Avg. Risk Weight	L^{HH} / L^{firms}	Implied Avg. Risk Weight
2013	0.630	0.692	0.630
2014	0.621	0.773	0.621
2015	0.614	0.810	0.617
Change 2013 to 2015 (%)	**-2.5**	17	**-2.0**

Table 5.5: Observed and implied change in average risk weights for low-capitalized banks. When calculating implied average risk weights we assume $\alpha^{hh} = 0.35$, $\alpha^{firm} = 1.0$, and $\alpha^{other} = 0.52$, as well as $\frac{A^{other}}{A} = 0.495$.

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[26]Loans to corporations with high credit ratings have assigned risk weights below 1.0. However, for non-IRB banks, Andersen and Winje (Norges Bank 2017) conclude that the average corporate risk-weight is close to 1.0.

[27]We start in 2013 because we do not have complete data on household lending for 2012.

5.5   Firm Level Analysis: Lending and Employment

So far we have been using bank level data, or loan level data aggregated to the bank level. In this section we use loan level data from tax reports. This has two advantages. First, it allows us to include firm fixed effects to strengthen our identification along the lines of Khwaja and Mian (2008). Second, it means that every firm is matched to its relationship bank(s), allowing us to evaluate whether there are adverse employment effects at the firm level.

5.5.1   Lending

To see why loan level data is useful for identification purposes, consider a bank i which lends to a firm j. While the lending amount is a result of both bank specific and firm specific factors, we only observe total equilibrium lending. Because firm specific factors are unobserved to us, we risk mis-measuring the effect of stricter requirements if supply and demand factors are correlated. With loan level data we can control for firm specific factors, thereby isolating the supply effects on total credit.

5.5.1.1   Stylized Model of Firm-Bank Lending

To inform our empirical specification, we construct a stylized model in the spirit of Khwaja and Mian (2008). The main difference is that we add labor to the firm problem and assume that the wage bill has to be financed with credit due to a cash-in-advance constraint. We also consider a slightly different shock from their shock to deposit financing. Adding labor to the firm problem enables us to derive a structural expression for employment growth as a function of credit supply factors.

Consider a bank i that lends to one firm j. We can think about the bank and firm being linked either through relationship-banking, or through their spatial locations (see Appendix D.2 for empirical evidence on these frictions). Bank profits are given by $\Pi_{i,t}^{b} = r_{i,t}L_{i,j,t}^{1-\beta} - (\bar{c}_t c_{i,t})^{\gamma} L_{i,j,t}$. The bank earns an interest rate $r_{i,t}$ from lending $L_{i,j,t}^{1-\beta}$, where β captures the degree of decreasing marginal returns to lending. The costs associated with lending are given by $(\bar{c}_t c_{i,t})^{\gamma}$, where $\bar{c}_t$ is a time-varying common cost component for all banks and c_{it} is a time-varying bank-specific cost component. Maximizing profits with respect to the lending volume, and taking logs, we get the following supply side expression $log(r_{i,t}) = \gamma log(\bar{c}_t) + \gamma log(c_{i,t}) - log(1 - \beta) + \beta log(L_{i,j,t})$.

Next, consider a firm j that borrows $L_{i,j,t}$ from one bank i. Firms require labor to produce output according to the production function $N_{j,t}^{1-\alpha}$ where α captures the degree of decreasing returns to scale in production. The price of the good produced is $p_{j,t} = \bar{\eta}_t \eta_{j,t}$ where $\bar{\eta}_t$ is a common factor across firms and $\eta_{j,t}$ is firm specific. Firms have no internal funds, and use bank loans to finance their wage bill. Due to unmodeled frictions in the credit market, $L_{i,j,t}$ dollars borrowed only finance $L_{i,j,t}^{\psi}$ of the wage bill, where $0 < \psi < 1$.[28] Credit thus serves the role of enabling the firm to

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[28]One way to microfound this is the presence of moral hazard, where the firm manager gets some private utility from diverting funds away from production. ψ would then capture the strength of the agency problem, with $\psi = 1$

finance more labor. Thus, $L_{i,j,t} = (W_t N_{j,t})^{\frac{1}{\psi}}$. We refer to this as the cash-in-advance constraint. Firm profits are given by $\Pi_{j,t}^f = \bar{\eta}\eta_{j,t}N_{j,t}^{1-\alpha} - r_{j,t}L_{i,j,t}$. Solving the cash-in-advance constraint for $N_{j,t}$, inserting it into the profit function, maximizing with respect to the borrowing amount L_{ijt}, and taking logs, we get the following demand side expression $log(r_{j,t}) = log(\psi(1-\alpha)) + log(\bar{\eta}_t) + log(\eta_{j,t}) - (1-\psi(1-\alpha))log(L_{i,j,t}) - (1-\alpha)log(W_t)$.

In equilibrium, the interest rate paid by the firm equals the interest rate received by the bank, so that $r_{it} = r_{jt}$. Combining the first order conditions for the bank and the firm, and solving for equilibrium lending we have that $log(L_{i,j,t}) = \frac{log(\psi(1-\alpha))+log(1-\beta)}{\beta+1-\psi(1-\alpha)} + \frac{log(\bar{\eta}_t)-\gamma log(\bar{c}_t)}{\beta+1-\psi(1-\alpha)} + \frac{1}{\beta+1-\psi(1-\alpha)}log(\eta_{j,t}) - \frac{\gamma}{\beta+1-\psi(1-\alpha)}log(c_{i,t}) - \frac{1-\alpha}{\beta+1-\psi(1-\alpha)}log(W_t)$. Taking the first difference of this expression, letting $\kappa \equiv \beta + 1 - \psi(1-\alpha)$ and denoting $\Delta log(X) = \frac{\Delta X}{X} = \tilde{X}$, with Δ being the change from $t-1$ to t, we get the expression in equation (5.10). The equation says that the (approximate) percentage change in lending $\tilde{L}_{i,j,t}$ is given by a common, economy-wide term, a firm-specific term, and a bank-specific term.

$$\tilde{L}_{i,j,t} = \underbrace{\frac{\tilde{\bar{\eta}}_t - \gamma\tilde{\bar{c}}_t - (1-\alpha)\tilde{W}_t}{\kappa}}_{\text{Common factors}} + \frac{1}{\kappa}\underbrace{\tilde{\eta}_{j,t}}_{\text{Firm-specific}} - \frac{\gamma}{\kappa}\underbrace{\tilde{c}_{i,t}}_{\text{Bank-specific}} \tag{5.10}$$

$$\tilde{N}_{j,t} = \psi\tilde{L}_{i,j,t} - \tilde{W}_t = \frac{\psi\tilde{\bar{\eta}}_t - \psi\gamma\tilde{\bar{c}}_t - [\psi(1-\alpha)+\kappa]\tilde{W}_t}{\kappa} + \frac{\psi}{\kappa}\tilde{\eta}_{j,t} - \frac{\gamma\psi}{\kappa}\tilde{c}_{i,t} \tag{5.11}$$

Our goal is to obtain an unbiased estimate of $\frac{\partial\tilde{L}_{i,j,t}}{\partial\tilde{c}_{i,t}} = -\frac{\gamma}{\kappa}$. Note that if $\gamma = 0$ we should not expect to find any effect on lending. To understand why, consider the banks marginal cost of lending, given by $(\bar{c}_t c_{i,t})^\gamma$. If $\gamma = 0$, the banks marginal funding cost is constant. This would be the case if the Modigliani-Miller theorem holds (Modigliani and Miller, 1958). An increase in capital requirements would have no impact on loan supply, as the bank can frictionlessly increase its share of equity financing. Hence, we can think of the case in which $\gamma = 0$ as a scenario in which a bank can react to a specific funding shock by shifting into other funding sources at no cost.

Equilibrium employment is given by the expression in equation (5.11). Here our goal is to obtain an unbiased estimate of $\frac{\partial\tilde{N}_{j,t}}{\partial\tilde{c}_{i,t}} = -\frac{\gamma\psi}{\kappa}$. The credit supply shock should have no effect on employment if the banks marginal funding cost is constant ($\gamma = 0$), or if there is no link between borrowing and employment ($\psi \to 0$).

5.5.1.2   Estimation

As seen from equation (5.10), the equilibrium lending outcome we observe each period is composed of firm-specific factors, bank-specific factors, and an economy-wide common term. The identification exercise is to isolate the supply effect from firm-specific factors. Note that if supply shocks $\tilde{c}_{i,t}$ are uncorrelated with demand shocks $\tilde{\eta}_{j,t}$, it would *not* be necessary to account for firm-specific factors in order to obtain an unbiased estimate of the impact of the cost shock. However, one might worry

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corresponding to the frictionless case and $\psi \to 0$ being a limiting case where the manager diverts all funds, and credit demand for a given wage bill goes to infinity.

that supply and demand shocks are in fact correlated due to firm-bank matching. For example, high-capitalized banks may be lending to firms with positive demand shocks. In this case, not accounting for firm-specific factors would lead us to overestimate the effect of the reform.

Our data covers a period of thirteen years, enabling us to use the flexible difference in difference approach to test whether firms borrowing from low-capitalized and high-capitalized banks have different outcomes prior to the reform. As documented in the previous section, whether a bank is low-capitalized or high-capitalized does not appear to have any impact on our outcome variables prior to the reform. However, one might still worry that firms borrowing from different bank types are different *conditional* on capital requirements being raised, for reasons unrelated to credit supply. This would be a natural concern if the shock we were studying was a large economic downturn like the financial crisis. In this case one might think that firms which looked identical prior to the crisis, could have underlying differences in risk profiles that only mattered conditional on a crisis occurring. We believe this to be of less concern in our case, as we are studying the implementation of a bank reform in normal economic times, designed by EU policy makers, which revealed no new information about bank quality. Regardless, we can address this potential issue by using loan level data and firm fixed effects. By looking at firms which borrow from multiple banks, we can compare lending outcomes for different levels of our cost shock, while holding firm characteristics fixed. The identifying assumption then becomes that credit demand is constant within a firm. That is, credit demand is firm-specific ($\eta_{j,t}$) rather than loan specific ($\eta_{j,i,t}$).

The traditional Khwaja and Mian (2008) estimation uses only cross-sectional variation, and so it is sufficient to include firm fixed effects. In our dynamic difference in difference framework, the analogous regression should include year×firm fixed effects. The identification is then based on firms which borrow from multiple banks, and whether they are more likely to borrow from their high-capitalized relationship bank(s) during the reform period. Note that our dynamic Khwaja and Mian (2008) estimation strengthens the identification relative to the traditional Khwaja and Mian (2008) estimation. By using pre-reform data, we can evaluate whether multiple-bank firms are more likely to borrow from their high-capitalized relationship bank(s) after the reform - *relative* to the pre-reform period. The regression we estimate is given by equation (5.12), where $\eta_{j,t}$ denotes year×firm fixed effects. Also note that the dependent variable is now the symmetric change in lending between a firm j and a bank i in year t.[29] We follow the literature in using the symmetric change to allow for entry and exit. Our proxy for the cost shock in equation (5.10), $\tilde{c}_{i,t}$, will be bank-capitalization levels *prior* to the reform. Any common factors across firms and banks - the first term in equation (5.10) - will be captured by the constant term and the time fixed effects. Hence, in our model framework, $\hat{\beta}^l$ should provide us with an unbiased estimate of $\frac{\partial \tilde{L}_{i,j}}{\partial \tilde{c}_i} = -\frac{\gamma}{\kappa}$.

$$\tilde{\Delta} L_{i,j,t} = \alpha + \sum_k \delta_k \mathbf{1}_{t=k} + \eta_{j,t} + \gamma_i^D D_i + \beta^l D_i \times I_t^{post} + \epsilon_{i,j,t} \tag{5.12}$$

[29] The symmetric change is defined as $\tilde{\Delta} X_t = \frac{X_t - X_{t-1}}{0.5\, X_t + 0.5\, X_{t-1}}$ and is bounded by -2 and 2.

5.5.1.3   Results

Including firm×year fixed effects is computational demanding, as we have a very high number of firms in our sample.[30] We therefore focus on a shorter time period around the reform to make the estimation manageable. We start by estimating equation (5.12) without firm fixed effects. The results are reported in the first column of Table 5.6. In line with the bank level results, we find that firms which borrow from low-capitalized banks have lower growth in lending in the post-reform period. The effect is significant at the one percent level, and says that firms which borrow from low-capitalized banks have on average 4.0 percentage points lower growth in lending in the post-reform period relative to the pre-reform period.

   In the second column we restrict the sample to only include firms with more than one bank connection in 2014.[31] These are the firms which can be used for identification when including firm×year fixed effects in the final column. While only including multiple bank firms reduces the sample substantially, precision falls only slightly. The coefficient increases in size and is still significant at the one percent level of significance.[32] Finally, we add firm×year fixed effects in the third column. The identification is now coming from within firm-year variation. The coefficient is as before significant at the one percent level, implying that firms which borrow from multiple banks have lower credit growth at their low-capitalized banks in the post-reform period.

	(1) $\tilde{\Delta}L_{i,j,t}$	(2) $\tilde{\Delta}L_{i,j,t}$	(3) $\tilde{\Delta}L_{i,j,t}$
$D_i \times I_t^{post}$	-3.950***	-9.887***	-15.13***
	(-4.52)	(-3.20)	(-2.82)
Time FE	yes	yes	yes
Type FE	yes	yes	yes
Firm FE	no	no	yes
Firms	all	multiple banks	multiple banks
Clusters	110	110	110
Observations	135,399	14,617	14,617

t statistics in parentheses, Std. err. clustered at bank level

* $p < .10$, ** $p < .05$, *** $p < .01$

Table 5.6: Restrictive difference-in-differences estimation - lending. Regression results from estimating equation (5.12)

   Two features of the regression results with and without firm×year fixed effects are worth high-

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[30]There are more than 137,000 unique firms in our cleaned sample, although the majority only borrows from a single relationship bank - and therefore cannot be used in the firm×year fixed effects regression.

[31]88 percent of the firms in our sample borrow from a single banks, 11 percent borrow from two banks, and 1 percent borrow from more than two banks.

[32]Firms which borrow from multiple banks tend to be larger in terms of number of employees. However, we have rerun the regression in equation (5.12) for small and large firms (not shown), and do not find support for large firms in general facing larger negative credit effects. If anything smaller firms have larger negative point estimates, although the difference is not statistically signficant. The (not significantly) stronger effect for multiple-bank firms may therefore seem puzzling. One potential explanation is that firms with multiple bank connections are more price sensitive, as they have multiple insider banks they can borrow from.

lighting. First, the increase in capital ratios is estimated to have a larger negative impact on corporate credit supply when we include firm fixed effects. This suggests that the implied correlation between supply and demand shocks is negative, causing us to underestimate the effect of higher capital requirements when not accounting for firm specific factors. In other words, low-capitalized banks lend to firms with higher credit demand, meaning that there is negative firm-bank matching. Second, we note that the difference in coefficient estimates is not statistically different. Hence, we cannot rule out that there is *no* firm-bank matching in our sample. We thus conclude that not accounting for firm specific factors would, *if anything*, bias our results towards zero.

5.5.2   Employment

We have documented a significant reduction in corporate lending growth from low-capitalized banks following the reform - both on the bank and firm level. Ultimately, the reason why we care about reductions in credit supply is that it might have adverse impacts on the real economy. We now investigate whether firms borrowing from low-capitalized banks have lower employment growth than other firms in the year following the reform. Note that we expect to find negative effects on employment growth only if there are quantitatively important frictions in firm-bank lending. That is, bank specific shocks will affect firms differentially if it is costly for firms to switch banks. This could be caused by relationship banking or geographical matching.[33] In Appendix D.2 we document that there are indeed substantial frictions in firm bank lending in our sample.

We again rely on the difference in difference framework to compare the employment outcomes of firms borrowing from high and low-capitalized banks. Because there is no variation in employment growth within firms, we cannot include firm fixed effects. However, the results from the previous section means that any bias from not controlling for firm specific factors would work against us.

In the upper row of Figure 5.9 we compare the growth in employment for firms borrowing from low-capitalized banks to that of firms borrowing from high-capitalized banks.[34] We see that while firms borrowing from low-capitalized banks tend to have higher employment growth - consistent with the negative matching found in the previous section - this is reversed in the year following the reform. Although this is suggestive of a negative employment effect, the difference is not statistically significant and the pre-reform trends do not look parallel. If we restrict the sample to exclude the very high and low-capitalized banks however, the pre-reform trends appear much more comparable. This is illustrated in the lower row of Figure 5.9, in which we compare quartile 2 banks (25th to 50th percentile) to quartile 3 banks (50th to 75th percentile) - and hence obtain a sample of more similar banks. Prior to the reform, firms borrowing from low-capitalized banks have slightly higher employment growth, with the difference between bank types being small and stable. After the reform however, employment growth for firms borrowing from low-capitalized banks falls, while employment growth for firms borrowing from high-capitalized banks increases. Hence, firms

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[33]See for example Sharpe (1990), Rajan (1992) or Holmstrom and Tirole (1997) for theory on relationship lending. See for example Brevoort, Wolken, and Holmes (2010) for empirical evidence on geographical lending patterns.

[34]Growth rates in employment are calculated as symmetric percentage changes, as several firms have zero employees in some years, which makes the standard percentage change undefined.

borrowing from low-capitalized banks have several percentage points lower growth in employment in the year following the reform.[35]

Figure 5.9: Employment. Banks are divided into groups based on their 2012 capital ratio. Left panels: Growth rates in employment for low-capitalized (25th to 50th percentile or 0th to 50th percentile) and high-capitalized (50th to 75th percentile or 50th to 100th percentile) banks. The growth rate for $year_t$ denotes the symmetric percentage change from $year_{t-1}$ to $year_t$. The solid red line marks the growth rate from 2012 to 2013 (the reform year). Right panels: Regression results from estimating equation (5.3) with dependent variable $Y_{j,t} = Employment_{j,t}$. Interaction coefficients $\gamma_{1,t}^{D}$ are plotted relative to year 2012. Standard errors are clustered at the bank level.

We estimate a version of the restrictive difference in difference equation, interacting a dummy for borrowing from a low-capitalized bank with a dummy for the year following the reform. The results are reported in Table 5.7. The first three columns use the full set of banks, comparing the employment growth of firms borrowing from banks with above and below median pre-reform capital ratios. While firms borrowing from low-capitalized banks are found to have lower employment growth in the year following the reform, the difference is not statistically significant. As previous literature has found smaller firms to be more vulnerable to bank specific shock, we split the sample

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[35]Note that we would not expect to see any effect in 2013 in this case. The reason is that quartile 2 banks did not start increasing the growth in capitalization levels until 2014 (while quartile 1 banks started in 2013), as illustrated in Figure D.3 in Appendix D.1. Also note that a reduction in credit supply to firms borrowing from low-capitalized banks could have positive spillover effects for firms borrowing from high-capitalized banks. If these firms are competing in the same markets, the firms with easy access to credit could benefit from less competition from the credit-constrained firms. Hence, the reduction in credit supply could have a negative impact on firms borrowing from low-capitalized banks and a positive impact on firms borrowing from high-capitalized banks. This seems consistent with the picture in the lower row of Figure 5.9.

into firms with above and below 25 employees (the sample average). As seen from the second column, there is no statistically significant effect for the large firms. However, there is a signficantly negative impact on small firms, as seen in the third column. Because the pre-trends looked more similar when excluding the very high and low capitalized banks, we also show results using this restricted sample. The results are reported in the three last columns of Table 5.7. Firms borrowing from low-capitalized banks are now found to have significantly lower employment growth in the year following the reform. Again, the coefficient increases in magnitude and statistical significance when only considering smaller firms. Note that in terms of our model - if the negative employment effects are larger for smaller firms - this would imply that the agency problems are worse for smaller firms (ψ is smaller).

	(1)	(2)	(3)	(4)	(5)	(6)
	$\Delta Empl_{j,t}$	$\Delta Empl_{j,t}$	$\Delta Empl_{j,t}$	$\Delta Empl_{j,t}$	$\Delta Empl_{j,t}$	$\Delta Empl_{j,t}$
$D_i \times I_t^{2014}$	-1.931	-0.486	-3.064***	-3.262**	-0.207	-4.717***
	(-1.55)	(-0.18)	(-2.97)	(-2.11)	(-0.06)	(-3.10)
Time FE	yes	yes	yes	yes	yes	yes
Type FE	yes	yes	yes	yes	yes	yes
Banks	all	all	all	25th-75th	25th-75th	25th-75th
Employment	all	25+	<25	all	25+	<25
Clusters	110	110	110	54	54	54
Observations	133,323	42,538	90,785	38,934	11,834	27,100

t statistics in parentheses, Std. err. clustered at bank level

* $p < .10$, ** $p < .05$, *** $p < .01$

Table 5.7: Restrictive difference-in-differences estimation - employment.

5.6 Further Evidence: Interest Rates and Aggregate Effects

We have documented a substantial reduction in asset growth for low-capitalized banks following the reform, and an especially large reduction in corporate credit supply. While we believe the flexible difference in difference results make a convincing case for the reduction in credit supply being supply-driven, we now provide additional support for this interpretation. While a negative shock to demand and supply have similar implications for lending volumes, they have opposite implications for the price of lending.

Although we do not directly observe interest rates, we observe the amount of outstanding debt and the amount of interest paid. In theory, it is therefore straightforward to back out the implied interest rate. In practice, because the data is annual, this procedure is likely to entail non-trivial measurement error. We address this by cutting the ten percent highest and lowest interest rates from our sample. The resulting interest rate estimates are illustrated in Figure D.2 in Appendix D.1. Our interest rate estimates seem consistent with aggregate interest rate data from Statistics Norway.[36]

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[36]The backed-out estimates follow the official numbers closely, although at a slightly higher level. This could be due

We aggregate the loan level interest rate data to bank level averages, and plot the resulting time series in Figure 5.10. The left panel compares interest rates for low-capitalized banks (below median) to that of high-capitalized banks (above median). High-capitalized banks have slightly higher interest rates prior to the reform, but this gap closes after the reform. Hence, low-capitalized banks see a relative increase in interest rates post-reform, consistent with the reduction in credit being supply driven. In the right panel of Figure 5.10 we exclude the 25 percent most and least capitalized banks from our sample. Hence, we compare quartile 2 banks (capital ratios in the 25th to 50th percentile) to quartile 3 banks (capital ratios in the 50th to 75th percentile). Using this more homogeneous group of banks, the results are even more striking. While quartile 2 and quartile 3 banks have almost identical interest rates prior to the reform, quartile 2 banks have consistently higher interest rates than quartile 3 banks in the post-reform period.
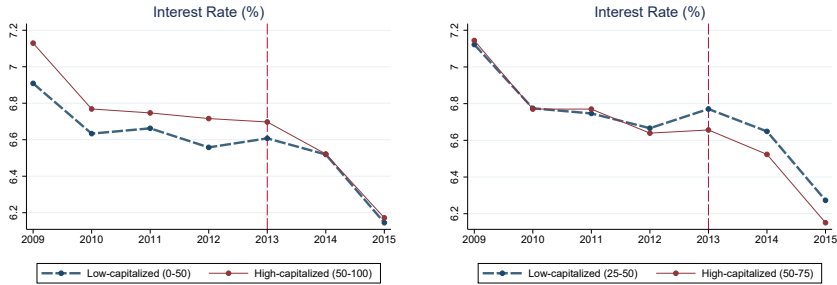
Figure 5.10: Interest Rates. Banks are divided into groups based on their 2012 capital ratios. Left panel: Interest rates for low-capitalized banks (below median) and high-capitalized banks (above median). Right panel: Interest rates for low-capitalized banks (25th to 50th percentile) and high-capitalized banks (50th to 75th percentile) .

While the results in Figure 5.10 are visually quite striking, the difference in interest rates between high-capitalized and low-capitalized banks are not statistically different from zero when using the flexible difference in difference approach specified in equation (5.3) (not shown). However, given the parallel trends observed, we are comfortable estimating the standard difference in difference equation specified in equation (5.4). The results are reported in Table 5.8. We find that low-capitalized banks have significantly higher interest rates than high-capitalized banks in the post-reform period.

to a consistent upward bias in our calculations, but could also be due to differences in the banks and firms included in the two data series. For example, the data from Statistics Norway include life insurance companies in their group of lenders, while these do not enter into our sample. Also, the Statistics Norway data include sole proprietorships in their group of borrowers, while our data does not. Including sole proprietorships is likely to reduce the average interest rate, as these are less risky borrowers due to unlimited liability. Regardless, the exact interest rate level is not of first order importance to us, as we are interested in differences (in differences) between the interest rates of high-capitalized and low-capitalized banks. As long as any bias in our interest rate estimates does not systematically vary across bank types - and differentially so pre- and post-reform - it would not alter our main conclusions.

	(1)
	$InterestRate_{it}$
$D_i \times I_t^{post}$	0.174**
	(2.03)
Time FE	yes
Type FE	yes
Clusters	110
Observations	329,024

t statistics in parentheses, Std. err. clustered at bank level

* $p < .10$, ** $p < .05$, *** $p < .01$

Table 5.8: Restrictive difference-in-differences estimation - Interest rates. Regression results from estimating equation (5.4).

5.6.1   Aggregate Effects

Our cross-sectional results can only identify a reduction in credit growth from low-capitalized banks *relative* to that of high-capitalized banks. In principle, it is therefore possible that high-capitalized banks were able to "pick up the slack" resulting from reduced credit supply from low-capitalized banks - leaving aggregate credit supply unaffected. We think this is unlikely due to three features of the data. First, because all the largest banks are low-capitalized, the combined market share of low-capitalized banks vastly exceeds that of high-capitalized banks. Hence, it seems practically difficult for high-capitalized banks to absorb all the excess demand. Second, as shown in Figure D.5 in Appendix D.3, we can explicitly calculate the number of firms which switch from low-capitalized bank to high-capitalized banks each year. There is no trend break in this series at the time of the reform, suggesting that the reform does not cause firms to switch banks. Finally and perhaps most importantly, the negative effect on employment provides indirect evidence that high-capitalized banks are not (fully) picking up the slack. If firms which were denied credit simply shifted to another bank, then there should be no differential effects on firm employment growth. Hence, we find it overwhelmingly likely that there was a reduction in aggregate credit supply. In Appendix D.3 we make use of some additional assumptions to back out plausible bounds for the impact on aggregate credit supply from our cross-sectional results.

5.7   Concluding comments

We have documented that low-capitalized banks increased their capital ratios mainly by reducing the growth in risk weighted assets. This was done primarily by reducing average risk weights. Consistent with the reduction in average risk weights, we found that low-capitalized banks reduced corporate lending relative to household lending. Back-of-the envelope calculations suggested that the shift from corporate lending to household lending could account for roughly 80 percent of the fall in average risk weights. Reassuringly, we also found that low-capitalized banks increased their interest rates, which supports the interpretation of the reduction in lending being supply driven.

Further, our results were robust to controlling for firm specific factors, suggesting that firm-bank matching is not an issue in our sample. The reduction in corporate credit supply was found to reduce employment growth for affected firms. Firms which borrowed from low-capitalized banks prior to the reform had lower employment growth following the increase in capital requirements.

We believe our results have implications for understanding the effectiveness of the countercyclical capital buffer, introduced in many countries as part of the Basel III regulation. While the main goal of this time-varying requirement is to make banks increase their capital ratios when times are good, it has also been suggested that the buffer can be used to smooth the credit cycle (Ministry of Finance, 2016). Norwegian authorities have a handful of indicators they look at when deciding whether the countercyclical capital buffer should be increased, one of which is rapid growth in household debt. If banks respond to higher capital requirements by reducing credit supply to the household sector, the countercyclical capital buffer could have a dampening effect on the credit boom. However, our results suggest that lending to the household sector is mostly unaffected by capital requirements. Hence, a dampening effect on the growth in household debt seems unlikely. It is important to highlight however, that this result is conditional on the current risk weights. Reducing the difference in risk weights between mortgages and corporate lending would likely lead to more of the reduction in credit supply being directed towards the household sector. More generally, the allocation of credit across sectors matters for the macro economy, and hence should be part of the discussion surrounding the design of capital requirements. Our finding that the reduction in credit supply is directed towards firms rather than households could be undesirable for several reasons. First, the Norwegian housing market was booming in 2013 and policy makers were concerned about unsustainable price growth (IMF, 2013). Hence, a reduction in household lending would probably have been preferred to the observed decline in corporate lending. Second and more generally, we found that the reduction in firm lending lead to lower employment growth. Relatedly, and as noted in Beck, Büyükkarabacak, Rioja, and Valev (2012), directing credit away from the corporate sector towards the household sector could have detrimental impacts on the long-term growth potential of the economy.

Chapter 6

Do stricter capital requirements make banks safer?

6.1 Introduction

The financial crisis of 2007 and 2008 was followed by broad regulatory reform intended to make the financial system more robust. Macroprudential regulation was introduced as an important part of the regulatory toolbox. In a broad sense, the main purpose of macroprudential regulation is to reduce systemic risk - the real economic cost of an under-capitalized banking sector. Perhaps the most important policy tool to address systemic risk has been capital requirements. For instance, Basel III - the global standard for capital regulation developed after the crisis - introduced a countercyclical capital buffer, a time-varying capital requirement intended to curb the buildup of systemic risk (Basel Committee on Banking Supervision, 2010). Furthermore, the European introduction of Basel III (CRD IV/CRR), introduced a specific "systemic risk buffer" for similar purposes. Even though the measurement of systemic risk has been advanced greatly over the recent years, to this date there is no empirical evidence on how effective such capital requirements have been in terms of decreasing systemic risk. In this paper I contribute to filling this gap.

Specifically, I investigate how capital requirements affect multiple measures related to banks systemic risk. I start by investigating the impact of increasing capital requirements on banks estimated conditional capital shortfall, or SRISK (Brownlees and Engle, 2016; Acharya, Engle, and Richardson, 2012). The fundamental idea behind SRISK is to provide an estimate for how well capitalized banks are in an economic downturn. I then investigate how capital requirements affect the fundamental determinants of systemic risk - debt, equity and how exposed banks equity are to large market declines, i.e. their marginal expected shortfall.[1]

Identifying the causal effect of increased capital requirements is challenging. Capital requirements are often imposed on all banks and as such prevents comparisons in outcomes between treated and non-treated banks. If that is not the case, capital requirements tend to be idiosyncratic and

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[1]There is a broad literature on measuring systemic risk. I rely primarily on these variables for reasons discussed in Section 6.3.

highly endogenous. To identify the effect of increased capital requirements on my outcome variables, I therefore follow an identification strategy pioneered by Gropp, Mosk, Ongena, and Wix (2018) and utilize a quasi-natural experiment commonly referred to in the literature as the "EBA capital exercise". During the EBA capital exercise, a subset of large European banks faced an increase in capital requirements. Treatment status of banks were based on their overall size. However, the cutoff for which banks were to be included or not were country-specific, depending on the market structures in each respective country. The EBA capital exercise therefore satisfies two fundamental identifying assumptions. First, selection into treatment was based purely on observables. Second, due to the country-specific thresholds there was a substantial overlap in terms of observables and which banks were selected into treatment and which banks were not.

I adopt two complementary approaches. First, I follow Gropp, Mosk, Ongena, and Wix (2018) by employing a bias-adjusted matching estimator which compares the outcomes for treated banks ("EBA banks") vs. non-treated banks ("non-EBA banks"). The idea behind this approach is to create a control group for each EBA bank based on observable characteristics. I then compare the change from pre- to post-reform in outcomes for treated banks and their matched control groups. As a second approach, I employ a flexible difference-in-differences where I compare outcomes for EBA banks with non-EBA banks prior to, during and after the EBA capital exercise. While this approach does not construct a specific control group for each treated bank, it has three important advantages relative to the matching estimator. First, the matching estimator can be confounded if EBA banks and their control groups are on different paths irrespective of treatment status. The flexible difference-in-differences explicitly allows me to test whether this is the case pre-reform. Second, the matching estimator is silent on the dynamic effects of increased capital requirements on my outcome variables. The flexible difference-in-differences allows me to investigate the dynamic effects of increased capital requirements on the outcome variables, by estimating monthly treatment effects pre-, during and post-reform. This is important in order to, for instance, gauge whether capital requirements have *persistent* effects on the outcomes I consider or whether the effects are short-lived. Third, it enables me to be agnostic about the exact timing of the policy intervention.[2]

The main finding of this paper is that capital requirements *increases* the systemic risk of banks. Put differently, EBA banks have significantly elevated systemic risk compared to non-EBA banks after the introduction of heightened capital requirements. The effects are also economically large - the EBA capital exercise lead to an increase in systemic risk of about 23 % relative to the pre-intervention mean. Investigating cross-sectional heterogeneity, I document how the increase in systemic risk is larger for banks with initially high systemic risk.

Next, I investigate *why* systemic risk increases. I show that EBA banks faces a substantial decline in the market value of capital over this period without a reduction in debt. Moreover, the long-run marginal expected shortfall of EBA banks increases. These normatively negative effects

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[2]The EBA announcement was preceded by a stress test in July. While the requirements eventually announced was significanty higher compared to analysts expectations, anecdotal evidence suggests that the stress test lead to some revisions of expected capital requirements. See "European bank stress test results raise doubts, hopes" (Euractiv, 18th of July 2011) and "Europe's banks face 9% capital rule" (Financial Times, 11th of October 2011).

are relatively persistent and lasts well into the post-reform period.

In order to ensure that the estimated effect of the EBA capital exercise is not confounded by the sovereign debt crisis, I preform multiple robustness tests. Among other things, I redo the analysis focusing on only northern European institutions and show that banks from GIIPS countries are not driving my results. In addition, I employ country × time fixed effects and show that even within a given country in a given year, banks facing a higher capital requirement experience a relative increase in systemic risk. I also conduct a Placebo test around the onset of the sovereign debt crisis by the end of 2009 / beginning of 2010 and show that there is no significant difference between EBA banks and non-EBA banks then.

Finally, I discuss what policy makers should take away from my findings and the existing literature on policy interventions and systemic risk. Greenwood, Hanson, Stein, and Sunderam (2017) put emphasis on recapitalizing banks following an adverse shock via emphasizing increases in *capital* rather than *capital ratios*. Berger, Roman, and Sedunov (2017) and Nistor Mutu and Ongena (2017) finds, in different settings, that capital injections decreases systemic risk. My findings, which shows that systemic risk increases when capital requirements increase, indicates that forcing banks to increase capital rather than increasing capital ratios are potentially more effective in terms of reducing systemic risk.

Literature review   This paper relates to the literature on how banks respond to increased capital requirements. Following the implementation of Basel III in Europe and Dodd-Frank in the U.S, there is a growing literature evaluating the effects of such regulation on bank behavior. For instance, Gropp, Mosk, Ongena, and Wix (2018) and Juelsrud and Wold (2017) investigate how banks respond to increased capital requirements and how banks responses ultimately transmit to the real economy.

In tandem with this literature on banks responses to regulation, a literature on the market-based measure of bank solvency and the measurement of systemic risk has emerged, see Benoit, Colliard, Hurlin, and Pérignon (2017) for a comprehensive survey. In what follows, I focus on the few measures most closely related to my paper. Brownlees and Engle (2016) measure a bank's systemic risk as its estimated capital shortfall conditional on a "crisis", i.e. a large market downturn. Other measures of systemic risk includes Adrian and Brunnermeier (2016)'s measure of changes in conditional Value at Risk. A recent literature on stress testing (see for instance Acharya, Pierret, and Steffen (2016) and a sequence of papers by the same authors) uses these new estimates of systemic risk to gauge the evolution of the riskiness of the global financial system over time.

My paper builds on recent research which combines the two strands of literature, by focusing on how systemic risk and other market-based measures of risk respond to policy interventions. Sarin and Summers (2016) highlight that market-based measures of bank risk has increased following the financial crisis. Chousakos and Gorton (2017) documents that banks Tobin's Q have remained low after the financial crisis. They argue that the low level of bank health is not explained by macroeconomic conditions. Instead they attribute it to repressive regulation. Bogdanova, Fender, Takáts, et al. (2018) on the other hand show that banks price-to-book ratios remain low following the crisis but that it the low level *can* be explained by macroeconomic conditions. Gao, Liao, and

Wang (2016) estimate the response of stock prices and bond yields for large financial institutions in the U.S after key events in the passage of the Dodd-Frank Act. They document that, on average, large financial institutions had negative abnormal stock returns and positive abnormal bond returns relative to small and medium sized financial institutions after key events in the legislative process of Dodd-Frank. They interpret these findings as the Dodd-Frank Act being effective in reducing large financial institutions risk-taking. Nistor Mutu and Ongena (2017) analyze the impact of several different policy measures on banks contributions and exposure to systemic risk. Specifically, they investigate the effects of recapitalizations, guarantees and liquidity injections on systemic risk measures and how the effects depend on banks risk profiles. Two of their findings is that recapitalizations reduces systemic risk in the short-run, while liquidity injections - especially at longer horizons - tend to elevate systemic risk. Berger, Roman, and Sedunov (2017), on the other hand, investigates the evolution of systemic risk for U.S banks that participated in the Troubled Asset Relief Program (TARP). They find that banks that participated in the TARP program had lower systemic risk post-intervention, and that this is driven by larger and ex.ante safer banks. This paper contributes to this literature by being the first paper, that I am aware of, to investigate how capital requirements - a key component of the regulatory reform - affect banks systemic risk.

6.2 Empirical methodology

6.2.1 Identification strategy

My identification strategy is to exploit a quasi-natural experiment known as the "EBA capital exercise". The EBA capital exercise constituted an increase in capital requirements for a subset of European banks. Specifically, the core tier 1 capital requirement increased from 5 % to 9% for 61 European banks. The aim of the regulatory change was to restore confidence in the European banking sector following the sovereign debt crisis.

The EBA capital exercise was announced by the European Banking Authority (EBA) on October 26, 2011, following the release of stress test results on the 15th of July. By the end of June 2012, all treated banks would have to adhere to the new requirement. The increased capital requirement was levied on large banks. Specifically, for each country banks were ranked based on their consolidated assets as of the end of 2010. The largest banks within each country were subject to the increase in capital requirements. Selection into treatment was based on a country-specific asset threshold. The asset threshold was set so that the increase in the capital requirement encompassed at least 50% of the national banking sectors. Due to regional variation in the structure of national banking sectors, this threshold rule implied relatively large variations in the number of banks that were affected by the increased requirements. Countries with banking sectors consisting of a few large banks would have few banks subject to the new requirement. Countries with many, smaller and homogeneous banks in terms of asset size would have many banks subject to the new requirement.

Identification in this paper comes from comparing outcomes between EBA banks and non-EBA banks. The EBA-capital exercise is an ideal set-up for investigating the effects of increased capital

requirements as it satisfies two fundamental identifying assumptions. First, since the selection into whether a bank would experience an increase in the capital requirement was based on its assets relative to a country-specific threshold, treatment was assigned purely based on observables. Hence, the assignment mechanism is known. Second, since the threshold for which banks were assigned treatment status or not was country-specific, there are substantial heterogeneity in treatment status conditional on bank size. To exploit these institutional features, I compare treated banks with non-treated banks using two complementary approaches.

6.2.1.1   Matching estimator

I follow Gropp, Mosk, Ongena, and Wix (2018) and start off by matching EBA-banks with non-EBA banks based on observables. Similar to Gropp, Mosk, Ongena, and Wix (2018) I employ an Abadie-Imbens bias-adjusted matching estimator (Abadie and Imbens, 2006), where each EBA-bank is matched with 4 similar control banks. "Similarity" between banks are based on the Mahalanobis-metric, which is a scale-invariant transformation of the Euclidean distance. Banks are matched according to their January 2010 assets, market capitalization and their estimated conditional capital shortfall (SRISK).[3]

Having matched a treated unit i with a control group $c(i)$ I estimate the change in outcome variable Y from the 12 months prior to the EBA-capital exercise (October 2010 - October 2011) to the 12 months after the EBA-capital exercise (July 2012 - July 2013). Y is the outcome variable I consider, which is either the estimated conditional capital shortfall (SRISK), market capitalization, debt or the long-run marginal expected shortfall of bank i. The difference for unit i from pre-treatment to post-treatment is denoted ΔY_i. Similarly, I compute the average change across unit i's control group and denote this $\Delta Y_{c(i)}$. The treatment difference for each treatment-control combination $m(i)$ is $\Delta Y_{m(i)} = \Delta Y_i - \Delta Y_{c(i)}$. To get the average treatment effect on the treated, I then average over all treatment-control combinations.

I adopt two matching strategies, in line with Gropp, Mosk, Ongena, and Wix (2018). First, I employ the matching estimator on the full sample of banks. Second, I employ the matching estimator on an "overlap-sample", consisting only of banks larger than the smallest EBA bank and smaller than the largest non-EBA bank. This alleviate some concerns that differences between EBA banks and non-EBA banks in the matching estimation is driven by bank size. Due to the reduced sample size, I employ a slightly different matching strategy in this sample. Rather than matching one treated bank to four control banks, I match one treated bank to one control bank, solely based on their January 2010 SRISK. The matching strategies are summarized in outlined in Table 6.1.

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[3]These variables, among a larger set of covariates, have a significant impact on the propensity score of being treated. Due to data availability, I match on slightly different covariates compared to Gropp, Mosk, Ongena, and Wix (2018).

Matching strategy	"Baseline"	"Overlap"
Sample Used	Baseline	Overlap
Number of matches	1:4	1:1
Matching covariates		
Total assets$_{2010}$	Yes	No
Total market capitalization$_{2010}$	Yes	No
SRISK$_{2010}$	Yes	Yes

Table 6.1: Matching strategies. This table outlines the baseline matching strategy, as well as an alternative matching strategy. The *baseline* sample includes all banks. The *overlap* sample includes all banks larger than the smallest EBA bank and smaller than the largest non-EBA bank. The number of matches refers to the number of control group banks matched to each EBA bank. All matching covariates except total assets are based on January 2010 values. Total assets are year-end 2009.

6.2.1.2   Flexible difference-in-differences

A different and complementary approach is to run a flexible difference-in-differences of the form

$$Y_{i,t} = \alpha + EBA_i + \sum_{k \neq \text{january 2010}} \beta_k \mathbf{1}_{t=k} + \sum_{k \neq \text{january 2010}} \gamma_k \left(\mathbf{1}_{t=k} \times EBA_i \right) + \epsilon_{i,t} \qquad (6.1)$$

where i indexes bank, $\mathbf{1}_{t=k}$ is year×month dummies and EBA_i is a dummy indicator for whether bank i is an EBA bank or not. An advantage with this methodology relative to the matching estimator in the previous section is that I do not have to impose a treatment period. Instead, the $\{\gamma_k\}_k$ captures the sequence of any time-varying differences between EBA banks and non-EBA banks. Absent any coincidental shocks to EBA-banks, γ_k 's during the treatment period can be interpreted as the effect of increased capital requirements on $Y_{i,t}$.

The flexible difference-in-differences has three advantages relative to the matching estimator outlined above. First, it allows me to test for whether EBA banks and non-EBA banks were on similar trends prior to the reform. This should at least give an indication of how reasonable the assumption of parallel trends is. Second, the flexible difference-in-differences allows me to estimate time-varying treatment effects. I can therefore answer questions on whether the effect is largest at the onset of the EBA capital exercise, underway, or later in the implementation period, as well as analyze whether the effects persist. Third, since the stress test results released in July resulted a stated need for recapitalization, it is likely that banks started to expect heightened capital requirements prior to the October announcement.[4] With the flexible difference-in-differences, I can be agnostic about the exact timing of the reform.

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[4]Anecdotal evidence suggests that analysts expected capital requirements of 7 % in order for European banks to be sufficiently capitalized following the release of the stress test results, see "European bank stress test results raise doubts, hopes" (Euractiv, 18th of July 2011). See also "Europe's banks face 9% capital rule" (Financial Times, 11th of October 2011).

6.2.1.3   Robustness

A threat to identification which neither of the two methodologies outlined above can account for, is contemporaneous shocks during the EBA capital exercise affecting EBA banks differently than non-EBA banks on average. An obvious concern is the sovereign debt crisis which takes place contemporaneously with my analysis. As discussed in Gropp, Mosk, Ongena, and Wix (2018), the sovereign debt crisis might have affected EBA banks differently through at least three potential channels: moral suasion by some governments (Ongena, Popov, and Van Horen, 2016), financial repression (Becker and Ivashina, 2017) or the ECBs liquidity program LTRO (Carpinelli and Crosignani, 2017; Van Rixtel and Gasperini, 2013). These concerns might be especially present for banks from GIIPS countries.[5] As Carpinelli and Crosignani (2017) and Van Rixtel and Gasperini (2013) documents, banks in these countries increased their holdings of domestic sovereign holdings during the Eurozone crisis, as well as made extensive use of ECBs LTRO program. In addition to the two empirical approaches outlined above, I therefore conduct multiple robustness exercises reported in Appendix E.3. Specifically, I focus on a sub-sample consisting only of non-GIIPS banks. I also rerun the estimating regressions employing a wide range of control variables.[6]

In addition to this, I redo the analysis including country $\times$year fixed effects. To the extent that the subsample analysis discussed in the previous paragraph does not fully remove banks relatively more exposed to the sovereign debt crisis, this approach provides an even tighter identification by comparing EBA banks to non-EBA banks within a given country within a given year. Finally, I conduct a Placebo test where I compare the evolution in systemic risk for EBA banks vs. non-EBA banks in the last half of 2009 and the first half of 2010, just at the onset of the sovereign debt crisis.

Since the market value of bank equity is an important determinant of a bank's systemic risk, I need to ensure that I am not contaminating my estimates with the impact of the release of the results from the EBA stress test three months prior to the increase in capital requirements. To do so, I therefore conduct informal event studies where I look at daily systemic risk estimates surrounding the EBA capital exercise announcement and the release of the stress test results. Moreover, I use the data from the stress test directly and show that EBA banks performed better in the stress test and hence any increase in the systemic risk in the months between the release of the stress test results and the EBA announcement is due to anticipated capital requirements and not due to market reevaluating the value of bank equity for EBA banks relative to non-EBA banks.

6.3   Data

6.3.1   Measuring systemic risk

There is a large and growing literature on measuring systemic risk, see Benoit, Colliard, Hurlin, and Pérignon (2017) for a survey. Broadly speaking, the literature can be divided into two - source-

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[5]Greece, Ireland, Italy, Portugal and Spain.

[6]I control for the 2010 values of total assets, leverage, long-run marginal expected shortfall and country fixed effects.

specific measures and global measures. Source-specific measures are typically rooted in a specific theoretical source of systemic risk. Empirical usage of such measures typically rely on confidential data. One example of this would be the focus on contagion of idiosyncratic bank failures in interbank networks, which requires detailed data on inter-bank exposures. Global measures typically rely on market data, at the cost of being somewhat broader in scope. However, due to their relatively easy-access, they have become increasingly popular. Due to data availability and the need to benchmark my results to other research on systemic risk and policy interventions in Section 6.6, I focus on global measures of systemic risk in this paper.

Within this sub-branch of the literature, there are multiple measures capturing distinct but closely related aspects of systemic risk. For instance, the concepts of marginal expected shortfall (MES) and systemic expected shortfall (SES) in Acharya, Pedersen, Philippon, and Richardson (2017) are extended and largely incorporated into the concept of *estimated conditional capital shortfall* (Acharya, Engle, and Richardson, 2012) or SRISK. From a practical point of view, the estimated conditional capital shortfall is an attractive measure of systemic risk, as it takes into account not only the return on equity a bank is expected to face during a general market downturn (the long-run marginal expected shortfall), but also how vulnerable it is to such reductions, i.e. how levered it is initially. The estimated conditional capital shortfall therefore produces a dollar-estimate of under capitalization for banks during an economic downturn, which has shown to be empirically informative when applied to for instance the financial crisis and the ultimate capital injections of U.S banks (Brownlees and Engle, 2016). For these reasons, I focus on the estimated conditional capital shortfall, as well as its various components such as the long-run marginal expected shortfall.[7]

6.3.2   Data description

For most of the analysis, I use monthly data on SRISK and its various components at the institution-level for the banks in my sample. The components of SRISK are market capitalization, the long-run marginal expected shortfall and debt. I focus on the period 2010 - 2014. My data contains 390 unique financial institutions. Out of these, 33 banks in my sample (see list in Appendix E.1) were given an additional capital requirement as a result of the EBA capital exercise.[8]

Before providing summary statistics, I briefly explain how the estimated conditional capital shortfall and the long-run marginal expected shortfall is measured.

Let $R_{t+1,t+h}^m$ denote the multi-period arithmetic market return between period $t+1$ and $t+h$.[9]

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[7]A different measure of the systemic risk of a financial institution is the ΔCoVaR (Adrian and Brunnermeier, 2016). This measure is an estimate of the value at risk for the entire financial system conditional on the institution being in distress. Acharya, Engle, and Richardson (2012) shows how the estimated conditional capital shortfall is easily compared to the ΔCoVaR under certain simplifying assumptions. Importantly, the marginal expected shortfall which is an important component of the estimated conditional capital shortfall is isomorphic to Adrian and Brunnermeiers *Exposure CoVar*. Hence, by also focusing on the long-run marginal expected shortfall, I am analyzing moments of the data closely related to ΔCoVaR.

[8]I follow Gropp, Mosk, Ongena, and Wix (2018) and exclude banks which were acquired during the sample period, banks which received capital injections and all banks with negative book value of equity. Furthermore, I only focus on banks for which estimates of conditional capital shortfall is available.

[9]I follow the notational convention that subscripts denote unit and time. However, for the returns over a given

A crisis is the event that $R_{t+1,t+h}^m < -40\%$, i.e. an episode where average market returns are below -40 % over a six month horizon. The long-run marginal expected shortfall is then defined as $\text{LRMES}_{i,t} \equiv -\mathbb{E}_t \left(R_{t+1,t+h}^i | R_{t+1,t+h}^m < -40\% \right)$. Intuitively, the long-run marginal expected shortfall is the period t expected return on the stock of bank i over a six month horizon if the general market return is below -40%. Importantly, the expectation is based only on information available up until period t. See Brownlees and Engle (2016) and Acharya, Pedersen, Philippon, and Richardson (2017) for the exact estimation procedure for obtaining the LRMES.

Define the capital shortfall of an institution i at time t as

$$CS_{i,t} \equiv \eta \left(D_{i,t} + W_{i,t} \right) - W_{i,t} \tag{6.2}$$

where $D_{i,t}$ is debt at time t and $W_{i,t}$ is the market-value of equity. The parameter η is meant to parametrize a prudential level of capital and is set to 5.5% for European banks.[10] A positive value of $CS_{i,t}$ indicates that the institution has a positive capital shortfall, whereas an institution with a negative $CS_{i,t}$ is considered adequately capitalized.

The estimated conditional capital shortfall - or SRISK - of an institution h periods ahead in time is then

$$\text{SRISK}_{i,t} = \mathbb{E}_t \left(CS_{i,t+h} | R_{t+1,t+h}^m < -40\% \right) \tag{6.3}$$

That is, an institutions SRISK is the estimated capital shortfall conditional on the overall market return over a six month horizon being below - 40 %.[11] The economic intuition for why this measures the systemic risk of an institution, is that if banks have a capital shortfall relative to their target leverage ratio η, they cut back on credit and sell of assets in order to delever. In normal times, this is less severe for the real economy as firms and households can obtain credit from other financing sources. During a general market downturn, however, it is less likely that other banks can "pick up the slack" and hence banks can impose costly externalities on the real economy.

6.3.3 Summary statistics

In Table 6.2 I report the summary statistics for the two groups (EBA banks and non-EBA banks). The table is based on averages for January 2010 or the year-end 2009. Not surprisingly, the two groups differ on several measures. Since EBA banks on average are larger banks, EBA banks have substantial higher SRISK, equity and assets. They also are more leveraged (average market-based leverage ratio of 26.5 vs. 10.7). The difference between EBA banks and non-EBA banks regarding

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time horizon I depart from that convention and use superscripts for the unit.

[10]The parameter essentially captures when an institution is "short on capital" relative to their target market leverage ratio.

[11]SRISK has since its introduction become a standard measure of systemic risk in academic research. See Berger, Roman, and Sedunov (2017), Buch, Krause, and Tonzer (2017), Nistor Mutu and Ongena (2017) and Weiß, Neumann, and Bostandzic (2014) for recent examples.

important characteristics emphasize the need for both employing a matching strategy, as well as explicitly testing for differential trends prior to the exercise.

	Mean	Median	*Non-EBA bank (N = 357)* Standard. dev.	p_{25}	p_{75}
SRISK (mill $)	923	-367	7 481	-931	99
Equity (mill $)	4 858	1 822	11 029	789	4 064
Debt mill $)	62 906	7 929	189 722	1 616	31 616
Assets (mill $)	67 764	10 412	198 411	3 102	34 932
LVG	10.7	5.1	16.2	2.2	12.7
LRMES	.36	.38	.12	.26	.45

	Mean	Median	*EBA bank (N = 33)* Standard.dev	p_{25}	p_{75}
SRISK (mill $)	26 004	8 090	37 770	2 762	22 920
Equity (mill $)	30 912	14 952	39 445	5254	51112
Debt (mill $)	744 329	282 270	888 028	106 048	1 328 368
Assets (mill $)	445 241	296 028	918 396	111 179	1 383 345
LVG	26.5	22	17.5	16	32.6
LRMES	.45	.48	.12	.41	.55

Table 6.2: Summary statistics. January 2010/end of 2009 values.

Matching on the January 2010 values of total assets, market capitalization and SRISK, however, yields substantially improved covariate balance between EBA banks and non-EBA banks. In Appendix E.2 I plot the distributions of covariates for EBA and non-EBA banks, for the raw sample and the matched sample under for both matching strategies.[12]

6.4   Empirical results

The empirical results in this section are structured in the following way. First, I analyze - using both the matching strategy and the flexible difference-in-differences approach - how the estimated conditional capital shortfall is affected by an increase in capital requirements. I then decompose the change in estimated conditional capital shortfall into changes in the market value of equity, debt and the long-run marginal expected shortfall.

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[12]In unreported regressions, I replace SRISK with $NRISK \equiv \dfrac{\text{SRISK}}{Equity}$. This normalization is used by Berger, Roman, and Sedunov (2017) to account for the fact that the distribution of SRISK is highly skewed. Results remain qualitatively unchanged.

6.4.1   Does capital requirements affect systemic risk?

The results from employing the matching estimator under the two matching strategies are presented in Table 6.3

Dependent variable	$\Delta SRISK$ (mill $)	
	Panel A: Baseline matching	*Panel B: Overlap matching*
Matching estimator	702.05***	646.54*
Std. error	266.65	347.30
p-value	0.008	0.06
Observations	382	195

Table 6.3: Changes in systemic risk. This table reports the estimates of how EBA-status affects changes in SRISK. Panel A focuses on differences in the change in SRISK between EBA banks and non-EBA banks under the baseline matching strategy. In the baseline strategy, each EBA-bank is matched to four non-EBA banks. Panel B uses the overlap matching strategies, where only banks with assets larger than the smallest EBA bank and smaller than the largest non-EBA bank are included. The row "matching estimator" reports the estimated average treatment effect based on the bias-corrected Mahalanobis matching estimator. Standard errors are Abadie&Imbens robust standard errors.

Focus on Panel A first, where I compare the outcomes between EBA banks and a matched control group for the full sample. The results suggest that EBA-banks had a *larger* change in the systemic risk measure pre- to post-treatment relative to similar non-EBA banks. On average, SRISK for EBA-banks increase with approximately 700 million USD from pre- to post-treatment relative to the control group.

In Panel B I report the results from a similar analysis, but where I focus on the overlap sample. The coefficient estimate is virtually unchanged, although it is somewhat less precisely estimated.

Next, I estimate the flexible difference-in-differences in equation (6.1). The coefficients γ_k captures time-varying differences between EBA banks and non-EBA banks. Their point estimates and 95% confidence intervals clustered at the country level are shown in Figure 6.1.

Figure 6.1: Coefficients γ_k from regressing equation (6.1). Vertical bars are 95 % confidence intervals clustered at the country level. October 2011 defined as period 0. Vertical lines correspond to the release of EBA stress test result, the actual introduction of heightened capital requirements in October 2011 and the first month after the EBA capital exercise (July 2012).

Prior to the EBA capital exercise, there are no statistically significant difference between EBA banks and non-EBA banks.[13] At the month of the stress test release and the subsequent period, EBA banks have significantly higher estimated capital shortfall than non-EBA banks.[14] On average, the SRISK for EBA-banks in my sample during the EBA capital exercise is 6 000 million USD higher than non-EBA banks, controlling for the average difference between the two types.[15] This corresponds to roughly 23 % of the pre-intervention mean. The difference remains elevated throughout the treatment period, and for the first three quarters after the reform.

6.4.1.1   Heterogeneity in responses

A natural question is whether the observed increase in systemic risk is present across all EBA banks or whether it is driven by a specific subset of banks. From a policy perspective, it is especially interesting to understand the effect of increased capital requirements on banks that have initial high systemic risk. In order to investigate this, I partition banks into two groups based on their initial systemic risk and whether it is below or above the median. I then estimate equation (6.1) for the different subgroups. The γ_k coefficients are shown in Figure 6.2.

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[13]The estimated coefficients are relative to the *average* difference between EBA banks and non-EBA banks.

[14]I discuss the timing of the increase and whether it stems from new information to market participants following the release of stress test results or whether it is an effect of the anticipated increase in requirements below in subsection 6.5.

[15]Note that in these regressions, the dependent variable is measured in *levels,* in contrast to the matching estimator. Moreover, I compare averages for all EBA banks vs. all non-EBA banks.
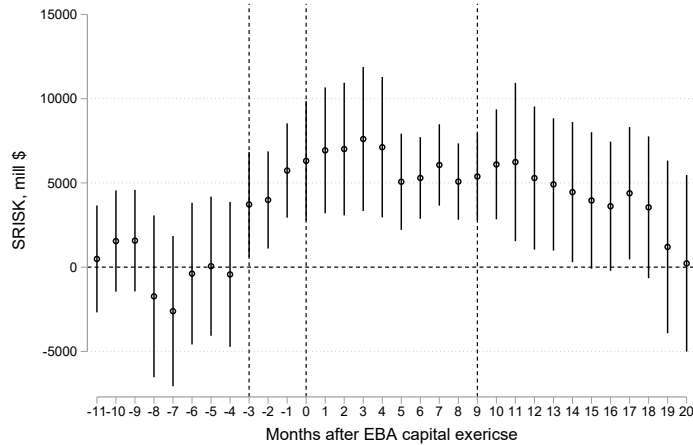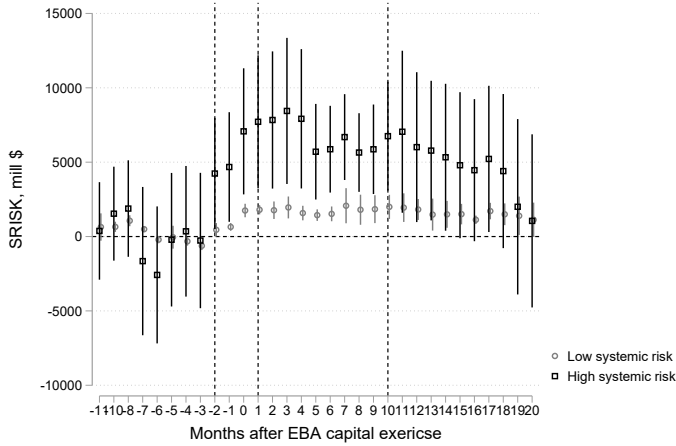
Figure 6.2: Coefficients γ_k from regressing equation (6.1). Vertical bars are 95 % confidence intervals clustered at the country level. October 2011 defined as period 0. Vertical lines correspond to the release of EBA stress test result, the actual introduction of heightened capital requirements in October 2011 and the first month after the EBA capital exercise (July 2012). Banks are split into two groups based on their January 2010 values of systemic risk.

In both cases, the point estimates are substantially and significantly higher for the banks with initial high systemic risk, compared to the banks with initially low systemic risk.

6.4.2 Why does capital requirements affect systemic risk?

As shown in Acharya, Pierret, and Steffen (2016), an institution i's SRISK in any given period t can be written as

$$\text{SRISK}_{i,t} = \eta D_{i,t} - (1 - \eta) W_{i,t} (1 - \text{LRMES}_{i,t}) \tag{6.4}$$

Hence, for an increase in the capital requirement κ, the total effect can be decomposed as

$$\frac{d\text{SRISK}_{i,t}}{d\kappa} = \eta \frac{\partial D_{i,t}}{\partial \kappa} - (1 - \eta)(1 - \text{LRMES}_{i,t}) \frac{\partial W_{i,t}}{\partial \kappa} + (1 - \eta) W_{i,t} \frac{\partial \text{LRMES}_{i,t}}{\partial \kappa} \tag{6.5}$$

That is, changes in the estimated conditional capital shortfall can decomposed into three components. The first component is changes in debt. More debt increases the estimated conditional capital shortfall as, for a given amount of equity, market leverage is higher. The second component is related to changes in the market value of equity. Keeping debt and risk (i.e. LRMES) fixed, a lower value of the bank's equity makes it more vulnerable to adverse return shocks and hence SRISK increases. Finally, the third component is related to changes in the riskiness of the bank's portfolio: a higher estimated long-run marginal expected shortfall increases SRISK. To decompose the increase in SRISK, I therefore repeat the analysis from above using these three variables as

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Dependent variable	$\Delta MCAP$ (mill \$)	
	Panel A: Baseline matching	*Panel B: Overlap matching*
Matching estimator	-644.74^{**}	-780^{**}
Std. error	285.21	371.30
p-value	0.02	0.04
Observations	382	195

Table 6.4: Changes in market capitalization. This table reports the estimates of how EBA-status affects changes in market capitalization. Panel A focuses on differences in the change in market capitalization between EBA banks and non-EBA banks under the baseline matching strategy. In the baseline strategy, each EBA-bank is matched to four non-EBA banks. Panel B uses the overlap matching strategies, where only banks with assets larger than the smallest EBA bank and smaller than the largest non-EBA bank are included. The row "matching estimator" reports the estimated average treatment effect based on the bias-corrected Mahalanobis matching estimator. Abadie & Imbens robust standard errors.

outcomes in my regressions.

Let us first consider the market capitalization of EBA banks vs. non-EBA banks. In Table 6.4, I report the result from the matching estimator applied to changes in market capitalization. As is clear from the table, EBA banks had a significantly lower market capitalization than non-EBA banks post-reform relative to pre-reform. Under the baseline strategy, the average reduction in market capitalization for EBA banks was approximately 640 million USD. The estimates from the second matching strategy yields somewhat larger effects. According to the estimates, in this sample market capitalization fall by 780 million USD for EBA banks relative to similar non-EBA banks.

In Table 6.5 and Table 6.6 I consider debt and LRMES as the dependent variable, respectively. With the exception of a weakly significant increase in debt in the full sample, there are no statistically significant differences between EBA banks and non-EBA banks.

Dependent variable	$\Delta Debt$ (mill \$)	
	Panel A: Baseline matching	*Panel B: Overlap matching*
Matching estimator	6773^{*}	4057
Std. error	3461	5696
p-value	0.06	0.71
Observations	382	195

Table 6.5: Changes in debt. This table reports the estimates of how EBA-status affects changes in debt. Panel A focuses on differences in the change in debt between EBA banks and non-EBA banks under the baseline matching strategy. In the baseline strategy, each EBA-bank is matched to four non-EBA banks. Panel B uses the overlap matching strategies, where only banks with assets larger than the smallest EBA bank and smaller than the largest non-EBA bank are included. The row "matching estimator" reports the estimated average treatment effect based on the bias-corrected Mahalanobis matching estimator. Abadie & Imbens robust standard errors.

Dependent variable	$\Delta LRMES$	
	Panel A: Baseline matching	*Panel B: Overlap matching*
Matching estimator	0.029	0.018
Std. error	0.029	0.022
p-value	0.32	0.86
Observations	382	195

Table 6.6: Changes in LRMES. This table reports the estimates of how EBA-status affects changes in LRMES. Panel A focuses on differences in the change in LRMES between EBA banks and non-EBA banks under the baseline matching strategy. In the baseline strategy, each EBA-bank is matched to four non-EBA banks. Panel B uses the overlap matching strategies, where only banks with assets larger than the smallest EBA bank and smaller than the largest non-EBA bank are included. The row "matching estimator" reports the estimated average treatment effect based on the bias-corrected Mahalanobis matching estimator. Abadie & Imbens robust standard errors.

Overall, the results from the matching estimators suggests that the primary reason for the increase in SRISK for EBA banks relative to non-EBA banks is a decrease in the value of the banks equity. Lower value of equity - and no change in debt - increases market-based leverage and make banks more vulnerable to drops in their asset values.

Next, to test for parallel trends and investigate the dynamic response of the outcome variables I estimate the flexible difference-in-difference from equation (6.1). I start by using market capitalization as the dependent variable. The coefficients γ_k is shown in Figure 6.3.

The figure echoes the results from the matching estimator. While there are no significant time-varying differences between EBA banks and non-EBA banks prior to the EBA capital exercise, EBA banks face a substantial reduction in their market capitalization following the release of the stress test results and the subsequent announcement of the reform. The difference lasts several months after the new capital requirement is fully phased in.
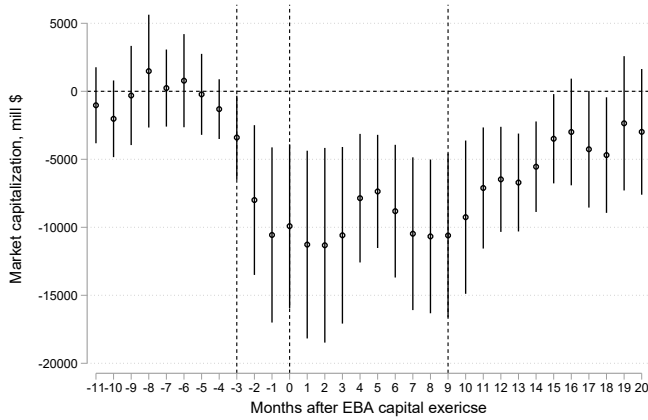
Figure 6.3: Coefficients γ_k from regressing equation (6.1) with market capitalization as dependent variable. Vertical bars are 95 % confidence intervals clustered at the bank level. October 2011 defined as period 0. Vertical lines correspond to the release of EBA stress test result, the actual introduction of heightened capital requirements in October 2011 and the first month after the EBA capital exercise (July 2012).

Next, consider LRMES as the dependent variable. The coefficients γ_k is now shown in Figure 6.4. Interestingly, and different from the previous section, EBA banks and non-EBA banks differ in their long-run marginal expected shortfall during the implementation of higher capital requirements. Specifically, EBA banks face an increase in their LRMES. From the figure, it is clear that the standard errors are relatively large, especially post-reform. Thus, comparing the average pre- and post-reform are bound to produce noisy estimates and can therefore at least partially explain the low power from applying the matching estimatior, where EBA and non-EBA banks are compared based on their average post-reform LRMES.
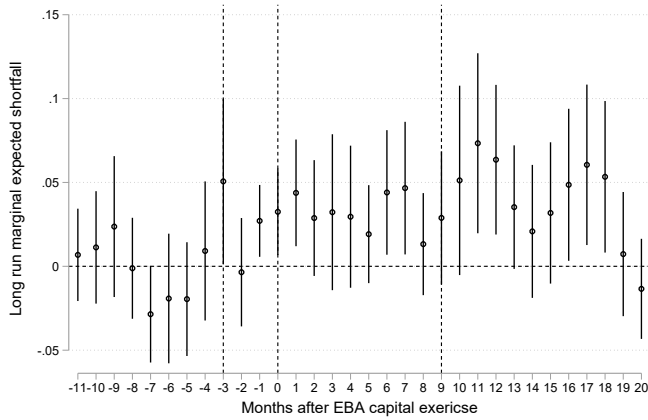
Figure 6.4: Coefficients γ_k from regressing equation (6.1) with LRMES as dependent variable. Vertical bars are 95 % confidence intervals clustered at the bank level. October 2011 defined as period 0. Vertical lines correspond to the release of EBA stress test result, the actual introduction of heightened capital requirements in October 2011 and the first month after the EBA capital exercise (July 2012).

Finally, consider the case where debt is the dependent variable. In this case, there standard errors are large and there are no significant differences between EBA banks and non-EBA banks.
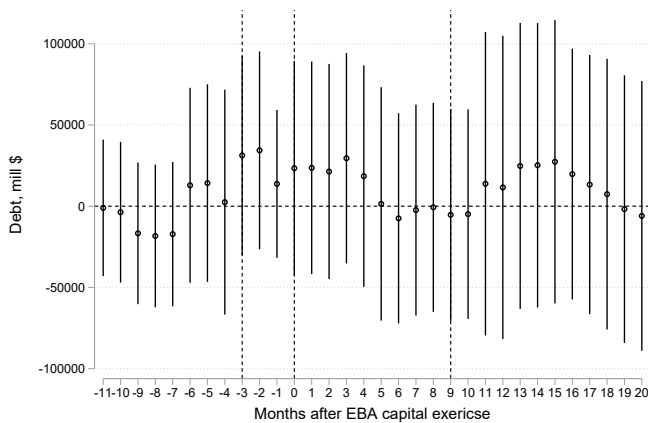
Figure 6.5: Coefficients γ_k from regressing equation (6.1) with debt as dependent variable. Vertical bars are 95 % confidence intervals clustered at the bank level. October 2011 defined as period 0. Vertical lines correspond to the release of EBA stress test result, the actual introduction of heightened capital requirements in October 2011 and the first month after the EBA capital exercise (July 2012).

6.5   Discussion

6.5.1   Underlying mechanism

As is clear from the previous analysis, there is a relative increase in systemic risk and a relative decrease in market capitalization for the EBA banks that starts prior to the EBA announcement. A crucial question is therefore why. One potential explanation is that the EBA capital exercises led EBA banks to issue new equity which, for instance due to asymmetric information between bank insiders- and outsiders, lead to a dilution of the stock price. Gropp, Mosk, Ongena, and Wix (2018) shows that there were limited equity issuances during the capital exercise period and that the equity issuances by EBA banks did not lead to negative announcement effects.[16] Hence, it is unlikely that equity issuances is the driving factor behind the decline in market capitalization for EBA banks over the capital exercise period.

   If not equity issuance can explain the decline in market value of bank equity, what can? To get closer to shedding light on this question, consider a simple framework with a representative investor buying stock in a bank. The standard asset pricing equation yields the stock price

$$p_t = \mathbb{E}_t \left[m_t x_{t+1} \right] \tag{6.6}$$

   where p_t is the stock price, m_t is stochastic discount factor of the investor and x_{t+1} is any payouts from the bank in the next period (i.e. the stock price p_{t+1} and any dividend payouts d_{t+1}). Normalizing the number of shares in the bank to 1 and assuming that the investor is risk-neutral, any variation in the market capitalization must come from changes in expected payouts. Why would capital requirements lead to revisions of investors belief about expected payouts? There are at least two possible explanations. First, capital requirements can induce banks to pay less dividends and lend less, and hence shift the path of future expected payouts from the bank. Second, even if banks do not respond to increased capital requirements, the requirements can contain informational content which leads investors to revise their expectations about the banks ability to pay out dividends in the future.[17] The latter is a relevant concern, given the observed increase in SRISK in the same month as the release of the EBA stress test results. While the EBA stress test encompassed a larger subset of banks relative to the EBA capital exercise, it could be that the stress test results were particularly bad for the EBA banks and hence lead investors to update their beliefs for this particular group. If that is indeed driving the results, then the increase in systemic risk is not *directly* about capital requirements but rather about the release of new information to market participants.

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[16]There were 7 equity issuances fro EBA banks and 6 from non-EBA banks.

[17]If investors are not risk-neutral, capital requirements can also affect stock prices via affecting the covariance between investors payoff and their stochastic discount factor.
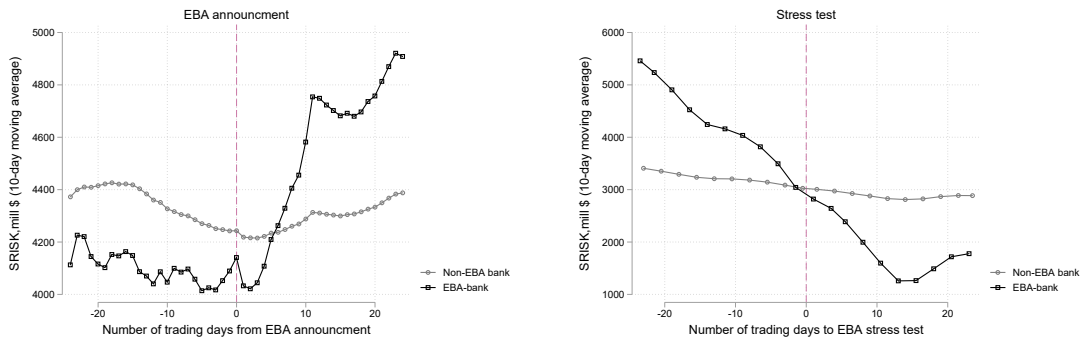
Figure 6.6: Systemic risk for EBA banks and non-EBA banks surrounding the EBA announcement on October 26th (left panel) and the release of the stress test results on July 15th.

6.5.1.1   Is the effect driven the EBA stress test and not the increased capital requirements?

Luckily, as systemic risk estimates rely on market data they can be analyzed on a day-to-day basis. Thus, the high-frequency nature of the data as well as the release of the actual stress test results allows me to dig deeper into this. To start off, I plot the evolution of systemic risk for EBA banks vs. non-EBA banks in a relatively tight window surrounding the (1) EBA capital exercise announcement (October 26th, 2011) and the (2) release of the stress test results (July 15th, 2011). The results are shown in Figure 6.6.

Focusing on the left panel first, around the EBA announcement there is a sharp increase in systemic risk for EBA banks compared to non-EBA banks, suggesting that increase of higher capital requirements had a direct impact on banks. This is in contrast to the results in the right panel, where I focus on the evolution of systemic risk around the release of the stress test results. There is no clear indication that EBA banks face an uptick in systemic risk immediately after the release of the stress test results, suggesting that the effect of the new information on the systemic risk measure was limited.

This is consistent with the actual results from the stress test. In fact, EBA banks on average had substantially better outcomes in the stress test compared to non-EBA banks. This is illustrated in Figure 6.6, where I plot the predicted percentage change in CT1 ratio in the stress test scenario for EBA banks and non-EBA banks. The median predicted CT1 change for EBA banks were -14 %, whereas it was -30 % for non-EBA banks, indicating that non-EBA banks were estimated to fare far worse during the stress scenario compared to non-EBA banks.

Taken together, the informal event study and the actual stress test results supports the notion that it was the anticipated increase in capital requirements that lead to the devaluation of bank equity rather than the informational content itself. Although the magnitude of the EBA capital exercise was unexpected, anecdotal evidence suggests that there were some revised expectations of
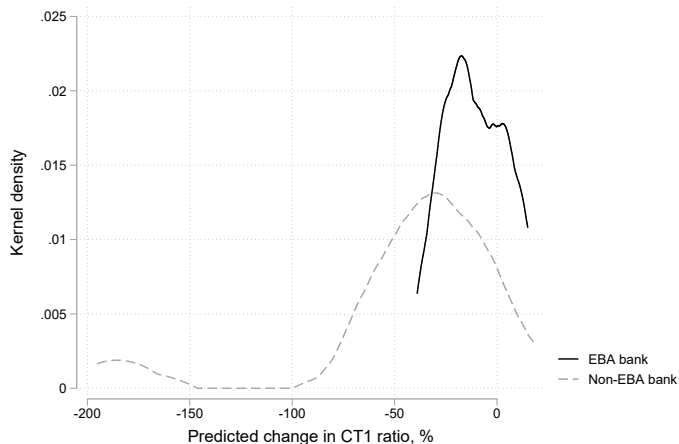
Figure 6.7: Density of predicted CT1 changes in July-stress tests, EBA banks vs. non-EBA banks.

higher capital requirements following the stress test. Hence, it is likely that some of the adjustment in the stock price and systemic risk measure that took place in the months prior to the EBA announcement was related to expected lower payouts from banks due to higher capital requirements.

6.5.1.2   The evolution of payouts from EBA banks

An important question is then why higher capital requirements ultimately reduce market capitalization. There are two suspects: lower dividend payouts in an effort to retain earnings and lower lending which ultimately implies lower profits. Although making precise statements about the nature of stock price movements is challenging, it is informative to compare dividends and asset growth for EBA banks. For instance, Gropp, Mosk, Ongena, and Wix (2018) documents a substantial decline in asset growth for EBA banks compared to non-EBA banks over the capital exercise period.

Consider the latter first. In Figure 6.8 I plot the change in market capitalization and the change in total assets over the EBA capital exercise period. Although it is not possible to make causal inference based on the figure, it at least supports the notion that there is a positive correlation between changes in market capitalization and changes in total assets. The relationship is statistically significant at conventional levels. Hence, it is possible that the reduction in market value is related to the reduction in assets due to the EBA capital exercise.

Next, consider the evolution of dividend payments for EBA banks vs. non-EBA banks shown in Figure 6.9. Inference is even more challenging here due to the annual frequency, but there are at least some indications that - while dividend payments for EBA banks and non-EBA banks follow similar evolution from 2010 to 2011, dividend payments for EBA banks slows down relative to the non-EBA banks.

Figure 6.8: Changes in assets and changes in market capitalization for EBA banks from the last month before the EBA capital exercise and the first month after (September 2011 - July 2012). Regression line has slope (standard error) of 0.10* (0.05).
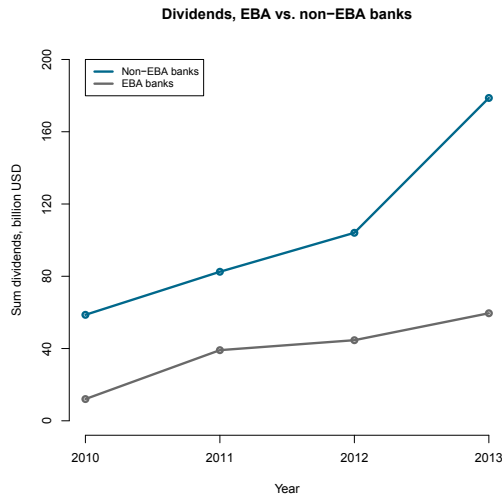
Figure 6.9: Evolution of aggregate dividends for EBA and non-EBA banks. Data: Thomson Reuters EIKON.

Hence, although I do not attempt to argue that lower lending and lower dividends *cause* the reduction in market capitalization, the observed reduction in market capitalization is at least consistent with a slowdown in payouts from EBA-banks.

6.5.2   Persistence

An important question from a policy standpoint is whether these normatively negative effects are persistent or not. Based on the estimated dynamic treatment effects it does not appear that the effect is permanent but rather relatively persistent. Unfortunately however, the research design does not allow me to make causal inference about the differences between EBA banks and non-EBA banks almost a year after the capital exercise has ended. For instance, in mid 2013 when the differences between EBA banks and non-EBA banks vanish, most European countries started to implement or prepare for implementing heightened capital requirements for all banks. This is arguably something that could have affected the control group more, given that the EBA banks already had built up a capital buffer of about 9 %. Hence, the "closing of the gap" between EBA banks and non-EBA banks could be due to heterogeneous shocks and not the effect of increased capital requirements on EBA banks tapering off. A perhaps more important final observation is that there is no indication from the preceding analysis that capital requirements ever lead to a *decrease* in systemic risk for EBA banks, which is an ultimate goal of the policy.

6.6   Recapitalizing weak banks

The empirical analysis in this paper has documented that an increase in capital requirements leads to an increase in systemic risk. The primary driver of this is a decrease in the market valuation of bank capital, combined with a slight increase in banks long-run marginal expected shortfall. A crucial question is therefore whether there are other policies that are more efficient in terms of reducing banks systemic risk.

Berger, Roman, and Sedunov (2017) and Nistor Mutu and Ongena (2017) analyzes the effects of direct recapitalizations on systemic risk during the TARP and a set of international recapitalizations, respectively. In both papers, the broad conclusion is that recapitalizations *decreases* systemic risk. Although their settings are different compared to mine, the overarching goals of the policy interventions are similar: increase the capitalization of banks in order to enable them to keep lending during a downturn and thereby impose less of a negative externality on the real economy. Their findings taken together with the results in this paper then suggests that recapitalizations are more effective in terms of reducing systemic risk compared to increasing capital ratios. This provides novel support for the key principles of bank capital regulation outlined in Greenwood, Hanson, Stein, and Sunderam (2017), which emphasizes the need to regulate capital rather than capital ratios, especially after adverse shocks.

As a final note, it is worth highlighting that this does not imply that capital requirements are welfare decreasing. First, capital requirements are likely to be more efficient in terms of achieving other goals from a social planner perspective, such as reducing the cost of bank overlending associated with deposit insurance. Hence, it is likely that policy makers should keep both tools in the toolbox, each addressing different concerns. Second, this increase in capital requirements happened during a major economic downturn where the marginal cost of equity is potentially high. Hence, it

is unclear whether similar increases in systemic risk in response to increased capital requirements would take place during normal economic times.

6.7   Concluding comments

In this paper, I investigate how capital requirements affect the solvency of financial institutions. Using the EBA capital exercise as a quasi-natural experiment, I found that an institution's estimated conditional capital shortfall *increases* when capital requirements increase. This effect is larger for initially risky banks. The primary reason for this decrease is that capital requirements reduces the market value of equity. There is also some evidence that the long-run marginal expected shortfall of treated institutions increase, indicating that capital requirements not only affects the valuation of banks but also the moments of their equity return distribution.

This paper raises important questions that are left for future research. An important question is whether the lack of improvement in systemic risk is something that was particular to this increase in capital requirements, or does it hold across different episodes of capital requirements increases in different countries. More broadly, evaluating theoretically and empirically how to recapitalize the financial system in a welfare maximizing way is of first-order importance for policy.

Appendix A

Appendix to Chapter 2

A.1   Additional analysis

Equilibrium definitions

We will use the following related equilibrium concepts that reflect the different information structures that we work with.

Definition A.1. (Exogenous information) A symmetric perfect Bayesian equilibrium in the exogenous information model consists of individual beliefs $\theta|\theta_i$, a rollover decision $a(\theta_i)$, an aggregate attack fraction, $A(\theta)$, and a bank policy pair $(d(\theta), g(\theta))$, such that 1) lenders' beliefs about θ given their signal θ_i satisfy Bayes' rule; 2) $a(\theta_i)$ maximizes individual expected utility (2.8), given individual beliefs; 3) the aggregate attack fraction is consistent with individual decisions, i.e. $A(\theta) = \int_i a(\theta_i)\, di$; and (4) $(d(\theta), g(\theta))$ maximizes the bank owner's utility (2.3), given the aggregate attack fraction $A(\theta)$.

For the endogenous information case, we have:

Definition A.2. (Endogenous information) A symmetric perfect Bayesian equilibrium in the endogenous information model consists of individual beliefs $\theta|d_i$, a rollover-decision $a(d_i)$, an aggregate attack fraction, $A(d)$, and a bank policy pair $(d(\theta), g(\theta))$, such that 1) lenders' beliefs about θ given their signal d_i satisfy Bayes' rule; 2) $a(d_i)$ maximizes individual expected utility (2.8), given individual beliefs; 3) the aggregate attack fraction is consistent with individual decisions, i.e. $A(d) = \int_i a(d_i)\, di$; and (4) $(d(\theta), g(\theta))$ maximizes the bank owner's utility (2.3), given the aggregate attack fraction.

Microfounded examples

One can treat the two examples jointly by assuming that $X_\theta \geq 0$ and $\rho_\theta \leq 0$ with one of the two inequalities strict for any θ. First of all, note that

$$\tilde{a}_l = \frac{1}{(1-\rho)X} > 0.$$

Thus, if the bank wants to hold an additional dollar in cash, it has to liquidate more assets. Also,

$$\tilde{a}_\theta = -\int_0^{\tilde{a}} \frac{\partial}{\partial \theta} \left[(1-\rho) X \right] da \cdot \tilde{a}_l < 0.$$

Thus, a bank with higher portfolio quality has to liquidate a smaller fraction of its portfolio. The remaining part of the bank's portfolio has a value of

$$v(\theta, l) = \int_{\tilde{a}}^1 X(a, \theta) da. \tag{A.1}$$

In this case,

$$v_l = -\frac{1}{1 - \rho(\tilde{a}, \theta)} < 0, \tag{A.2}$$

which is the opportunity cost to the bank of marginally increasing its cash holdings. Intuitively, it is inversely related to the liquidation discount of the asset. An asset with no liquidation discount is a perfectly substitutable to cash, while a fully illiquid asset is never liquidated. Also, note that $v_{ll} \propto -\rho_a \tilde{a}_l < 0$. Intuitively, to obtain an additional dollar of liquidity, the bank has to liquidate assets with larger discounts. Furthermore,

$$v_\theta = \int_{\tilde{a}}^1 X_\theta da - X(\tilde{a}, \theta) \tilde{a}_\theta > 0.$$

The asset value at $t = 2$ is increasing in θ for two reasons. First, a bank with higher θ may have assets with higher expected payoffs. Second, a bank with higher θ may have to liquidate fewer assets to obtain the same amount of cash. Finally,

$$v_{l\theta} \propto -(\rho_\theta + \rho_a \tilde{a}_\theta) > 0. \tag{A.3}$$

Therefore, a bank with higher θ has a lower opportunity cost of increasing cash holdings, since its assets have lower discounts, and also, since it has to liquidate fewer assets.

Exogenous information and two dividend levels

The following proposition characterizes the unique equilibrium with exogenous information.

Proposition A.1. *(Exogenous information) Suppose that lenders have a diffuse prior over $\theta \in \mathbb{R}$ and that assumption A1 holds. There exists a unique equilibrium, which is in monotone strategies and is given by a failure cutoff θ_f, a strategic cutoff $\hat{\theta}$, such that a lender with signal x attacks iff $x \leq \hat{\theta}$ and the bank fails iff $\theta \leq \theta_f$. Additionally, let $\theta_0 \equiv \bar{\ell}^{-1}(m)$, $\tilde{\theta} \equiv \bar{\ell}^{-1}(m+p)$, and let θ_a solve*

$$\lambda m = v(\theta_a, p). \tag{A.4}$$

If $\lambda m \geq v\left(\tilde{\theta}, p\right)$, then $\theta_f = \tilde{\theta}$, and the optimal bank dividend policy satisfies

$$d\left(\theta\right) = \begin{cases} m & , \theta \in [\theta_0, \infty) \\ 0 & , o.w. \end{cases}.$$

Otherwise, $\theta_f = \theta_a < \tilde{\theta}$, and the optimal bank dividend policy satisfies

$$d\left(\theta\right) = \begin{cases} m & , \theta \in [\theta_0, \theta^f) \cup [\theta_1, \infty) \\ 0 & , o.w. \end{cases},$$

where $\theta_1 > \theta_f$ sovles

$$\lambda m + v\left(\theta_1, A\left(\theta_1, \hat{\theta}\right) + m\right) = v\left(\theta_1, A\left(\theta_1, \hat{\theta}\right)\right). \tag{A.5}$$

In either case, $\hat{\theta}$ is the solution to

$$A\left(\theta_f, \hat{\theta}\right) = p. \tag{A.6}$$

Proof. We show this result in several steps. First we show that for every strategic cutoff $\hat{\theta}$, there is a unique $\theta_f \in (\underline{\theta}, \bar{\theta})$, such that the bank fails for $\theta \leq \theta_f$ and survives otherwise. Second, we characterize the bank's optimal policies. Next we show some properties of $\hat{\pi}\left(x, \hat{\theta}\right)$ and conclude that there is a unique strategic cutoff $\hat{\theta}$. Finally, we argue using an interim rationalizability argument that the monotone strategy equilibrium is the unique equilibrium of the game.

Bank's problem. Consider the bank's optimization problem, given by

$$\max_{d,g} W(d, g, \theta, \hat{\theta}) = \lambda d + \mathbf{1}_{\left\{g \geq A(\theta, \hat{\theta})\right\}} v(\theta, g + d) \tag{A.7}$$

$$s.t. \ g + d \leq \bar{\ell}\left(\theta\right),$$

$$d \in \{0, m\},$$

where

$$A\left(\theta, \hat{\theta}\right) = \Phi\left(\sqrt{\alpha_\theta}\left(\hat{\theta} - \theta\right)\right).$$

There are several cases to consider.

1. Suppose that $\bar{\ell}\left(\theta\right) < A(\theta, \hat{\theta})$. Therefore, the bank cannot survive even if it uses the maximum available liquid assets $\bar{\ell}\left(\theta\right)$. In that case it is optimal for the bank to choose the highest feasible dividend payment, i.e. $d\left(\theta\right) = \begin{cases} m & , \ m \leq \ell\left(\theta\right) \\ 0 & , \ o.w. \end{cases}$.

2. Suppose that $\bar{\ell}\left(\theta\right) \geq A(\theta, \hat{\theta})$ and $\bar{\ell}\left(\theta\right) - m < A(\theta, \hat{\theta})$. Therefore, survival is feasible provided that the bank does not pay out m in dividends. Suppose that $m > \bar{\ell}\left(\theta\right)$. Since choosing $d = 0$ is always feasible, and the bank survives if it pays 0, it always prefers survival. Suppose instead that $m \leq \bar{\ell}\left(\theta\right)$. In that case, the bank chooses between paying out m and failing or paying out 0 and

surviving. It chooses the former if

$$\lambda m > v\left(\theta, A\left(\theta, \hat{\theta}\right)\right).$$

As we show below, at θ_f, $A\left(\theta_f, \hat{\theta}\right) = p$, so Assumption A1 implies that at θ_f, $m < A\left(\theta_f, \hat{\theta}\right) \le \bar{\ell}(\theta_f)$. This in turn implies that $m < \bar{\ell}(\theta)$ whenever $\bar{\ell}(\theta) \ge A(\theta, \hat{\theta})$. Therefore, only the case $m \le \bar{\ell}(\theta)$ is relevant.

3. Suppose that $\bar{\ell}(\theta) - m \ge A(\theta, \hat{\theta})$. Therefore, survival is feasible even if the bank pays out m. In that case, the bank chooses to survive and pays m if

$$\lambda m + v\left(\theta, A\left(\theta, \hat{\theta}\right) + m\right) > v\left(\theta, A\left(\theta, \hat{\theta}\right)\right).$$

Next, define $\tilde{\theta}\left(\hat{\theta}\right)$ as the solution to

$$\bar{\ell}\left(\tilde{\theta}\right) = m + A\left(\tilde{\theta}, \hat{\theta}\right) \tag{A.8}$$

Therefore, $\tilde{\theta}$ gives the value of fundamentals at which a bank can both pay out m and survive. Also, define $\theta_a\left(\hat{\theta}\right)$ as the solution to

$$\lambda m = v\left(\theta_a, A\left(\theta_a, \hat{\theta}\right)\right). \tag{A.9}$$

Therefore, θ_a gives the value of fundamentals at which a bank is indifferent between paying out m and failing or paying out 0 and surviving.

By the definition of $\tilde{\theta}$, $\theta_f\left(\hat{\theta}\right) \le \tilde{\theta}$, since for $\theta > \tilde{\theta}$ the bank always chooses to survive. Since $v\left(\theta, A\left(\theta, \hat{\theta}\right)\right)$ is increasing in θ, it follows that if at $\tilde{\theta}$, $\lambda m \ge v\left(\tilde{\theta}, A\left(\tilde{\theta}, \hat{\theta}\right)\right)$, then for $\theta < \tilde{\theta}$, the bank is better off failing even when it is feasible to survive, and so $\theta_f\left(\hat{\theta}\right) = \tilde{\theta}$. Also, it is better off paying m whenever feasible. Also, notice that

$$\frac{\partial}{\partial \theta}\left[v\left(\theta, A\left(\theta, \hat{\theta}\right) + m\right) - v\left(\theta, A\left(\theta, \hat{\theta}\right)\right)\right] = \left[v_\theta\left(\theta, A\left(\theta, \hat{\theta}\right) + m\right) - v_\theta\left(\theta, A\left(\theta, \hat{\theta}\right)\right)\right] + $$
$$+ \left[v_l\left(\theta, A\left(\theta, \hat{\theta}\right) + m\right) - v_l\left(\theta, A\left(\theta, \hat{\theta}\right)\right)\right]\frac{\partial}{\partial \theta}A\left(\theta, \hat{\theta}\right) > 0$$

by the properties of $v(\theta, l)$, and since $A\left(\theta, \hat{\theta}\right)$ is monotone decreasing in θ. Therefore, for $\theta > \tilde{\theta}$, $\lambda m + v\left(\theta, A\left(\theta, \hat{\theta}\right) + m\right) > v\left(\tilde{\theta}, A\left(\tilde{\theta}, \hat{\theta}\right)\right)$ and the bank is better off paying m.

On the other hand, if at $\tilde{\theta}$, $\lambda m < v\left(\tilde{\theta}, A\left(\tilde{\theta}, \hat{\theta}\right)\right)$, then $\theta_f\left(\hat{\theta}\right) = \theta_a \le \tilde{\theta}$. In that case the bank pays m whenever feasible for $\theta \le \theta_f$, and it pays 0 for $\theta \in (\theta_f, \theta_1)$, and m for $\theta > \theta_1$. Therefore,

$$\theta_f\left(\hat{\theta}\right) = \begin{cases} \tilde{\theta}\left(\hat{\theta}\right) & , \tilde{\theta} \le \theta_a \\ \theta_a\left(\hat{\theta}\right) & , \tilde{\theta} > \theta_a \end{cases}. \tag{A.10}$$

Finally, notice that in either case, $0 \leq \frac{\partial \theta_f}{\partial \hat{\theta}} < 1$ whenever θ_f is differentiable. To see this, note first that by the implicit function theorem, $\frac{\partial \hat{\theta}}{\partial \theta} = \frac{A_{\hat{\theta}}}{\bar{\ell}' - A_\theta} = \frac{A_{\hat{\theta}}}{\bar{\ell}' + A_{\hat{\theta}}}$, where the second equality comes from using $A_{\hat{\theta}} = -A_\theta$. Therefore, $0 \leq \frac{\partial \hat{\theta}}{\partial \theta} < 1$ by the properties of A and $\bar{\ell}$. Similarly, $\frac{\partial \theta_a}{\partial \hat{\theta}} = -\frac{v_l A_{\hat{\theta}}}{v_\theta + v_l A_\theta} = \frac{v_l A_\theta}{v_\theta + v_l A_\theta}$, so again $0 \leq \frac{\partial \theta_a}{\partial \hat{\theta}} < 1$ by the properties of v and A.

Lender's problem. We have

$$
\begin{aligned}
\hat{\pi}(x, \theta_f) &= p - \Pr\{g > A | x\} \\
&= p - \Pr\{\theta > \theta_f | x\}.
\end{aligned}
$$

With a diffuse prior over θ, Bayes' rule implies that $\theta | x \sim N\left(x, \alpha_\theta^{-1}\right)$. Therefore,

$$
\Pr\{\theta > \theta_f | x\} = 1 - \Phi\left(\sqrt{\alpha_\theta}\left(\theta_f - x\right)\right) = \Phi\left(\sqrt{\alpha_\theta}\left(x - \theta_f\right)\right).
$$

Therefore, $\hat{\theta}\left(\theta_f\right)$ satisfies

$$
\Phi\left(\sqrt{\alpha_\theta}\left(\hat{\theta}\left(\theta_f\right) - \theta_f\right)\right) = A\left(\theta_f, \hat{\theta}\left(\theta_f\right)\right) = p. \tag{A.11}
$$

By the implicit function theorem this condition defines an implicit relation between $\hat{\theta}$ and θ_f, such that $\frac{\partial \hat{\theta}}{\partial \theta_f} = -\frac{A_\theta}{A_{\hat{\theta}}} = 1$.

Thus, $\hat{\pi}$ is continuously differentiable in both arguments, strictly increasing in θ_f and strictly decreasing in x. Furthermore, $\lim_{x \to -\infty} \hat{\pi}(x, \theta_f) = p > 0$ and $\lim_{x \to \infty} \hat{\pi}(x, \theta_f) = p - 1 < 0$.

Unique monotone equilibrium. Therefore, a monotone equilibrium of this economy is given by the intersection of condition (A.10) and the relation $\hat{\theta}\left(\theta_f\right)$ implicitly defined by condition (A.11) in $(\hat{\theta}, \theta_f)$-space. Both are continuous and increasing but the first relation has a slope strictly less than one, while the second relation has a slope equal to one. Therefore, the two relations can cross at most once.[1]

Rationalizability. We now show that the unique monotone equilibrium is also the unique equilibrium of this economy by using iterated elimination of strictly dominated strategies. Define $h\left(\hat{\theta}\right)$ implicitly via $\hat{\pi}\left(h\left(\hat{\theta}\right), \theta_f\left(\hat{\theta}\right)\right) = 0$. This function is continuous, since the functions $\hat{\pi}$ and θ_f are continuous. It is also increasing in $\hat{\theta}$, since θ_f is increasing in $\hat{\theta}$ and $\hat{\pi}$ is decreasing in its first argument and increasing in the second argument. Also, notice that a fixed point of $h\left(\hat{\theta}\right)$ gives a monotone equilibrium for this economy. Since that monotone equilibrium is unique, it follows that $h\left(.\right)$ has a unique fixed point.

The most optimistic scenario for any lender is that only banks with $\theta < \underline{\theta}$ fail. Let $\Pr(\theta < \underline{\theta} | x_i)$ denote the probability of bank failure in this case for a lender that observes signal x_i. Since $\Pr(\theta < \underline{\theta} | x_i)$ is continuous and strictly decreasing in x_i with $\lim_{x \to -\infty} \Pr(\theta < \underline{\theta} | x_i) = 1$ and $\lim_{x \to \infty} \Pr(\theta < \underline{\theta} | x_i) = 0$, there exists a signal $\underline{x}$ such that $\Pr(\theta < \underline{\theta} | \underline{x}) = p$. For $x_i \leq \underline{x}$ it is strictly dominant to choose $a_i = 1$. Similarly, one can establish the existence of a $\bar{x}$, which gives the signal

---

[1] Also standard fixed point results ensure equilibrium existence.

of an indifferent agent in the most pessimistic scenarios when only banks with $\theta > \bar{\theta}$ survive.

Next, set $x_0 = \underline{x}$. Therefore, from the definition of $h(.)$, running for signal $x_i \leq x_1 \equiv h(x_0)$ is strictly dominant. By the properties of the function $h(\cdot)$, we can therefore construct a sequence $\{x_n\}_{n=0}^\infty$ defined recursively by $x_n = h(x_{n-1})$, which is increasing. Furthermore, it's bounded above by $\bar{x}$. Therefore, this sequence converges and by continuity of h it converges to the unique fixed point of $h(\cdot)$, $\hat{\theta}$. Similarly, once can construct a sequence starting from $x_0 = \bar{x}$, which is decreasing and bounded below by $\underline{x}$. That sequence then also converges to the unique fixed point of $h(\cdot)$. $\square$

We also have the following immediate corollary.

Corollary A.1. *In the limit, as $\alpha_\theta \to \infty$, $\hat{\theta} \to \theta_f$. Furthermore, θ_f still satisfies $\theta_f = \tilde{\theta}$ or $\theta_f = \theta_a$ depending on whether $\lambda m \geq v\left(\tilde{\theta}, p\right)$.*

Proof. We use (A.6) to write $\hat{\theta} - \theta_f = -\dfrac{1}{\sqrt{\alpha_\theta}}\Phi^{-1}(p-1)$. Thus $\alpha_\theta \to \infty$ implies that $\hat{\theta} \to \theta_f$. Finally, notice also that either of the two equations that pin down θ_f do not depend on α_θ. $\square$

Thus the precision of private information that lenders receive has no effect on the failure threshold. What it does affect is only the cutoff θ_1 at which surviving banks pay dividends in the case when $\lambda m < v\left(\tilde{\theta}, p\right)$.

Endogenous information and two dividend levels

For a given cutoff $\hat{d}$, the solution to the bank's problem is summarized in Lemma A.1.

Lemma A.1. *(Bank problem). Suppose assumption A1' holds and that lenders follow a monotone strategy with cutoff $\hat{d}$. Then there exists a unique θ_f such that the bank fails iff $\theta \leq \theta_f$. If $A(m, \hat{d}) + m \leq A(0, \hat{d})$ or $A(m, \hat{d}) + m > A(0, \hat{d})$ and $\lambda m \geq v\left(\tilde{\theta}, A(0, \hat{d})\right)$ (Case 1'), $\theta_f = \tilde{\theta} \equiv \bar{\ell}^{-1}\left(m + A\left(m, \hat{d}\right)\right)$, and the optimal bank dividend policy satisfies*

$$d(\theta) = \begin{cases} m & , \theta \in [\theta_0, \infty) \\ 0 & , o.w. \end{cases}, \tag{A.12}$$

where $\theta_0 \equiv \bar{\ell}^{-1}(m)$. Otherwise, (Case 2') $\theta_f = \theta_a$, where θ_a solves

$$\lambda m = v\left(\theta_a, A(0, \hat{d})\right), \tag{A.13}$$

and banks with $\theta \in \Theta_1 = [\theta_0, \theta_f] \cup [\theta_1, \infty)$ pay dividends, where θ_1 satisfies $\lambda m + v\left(\theta_1, A(m, \hat{d}) + m\right) = v\left(\theta_1, A(0, \hat{d})\right)$. In both cases $\dfrac{\partial \theta_f}{\partial \hat{d}} \geq 0$.

Proof. Consider the bank's optimization problem, given by

$$\max_{d,g} W(d, g, \theta, \hat{d}) = \lambda d + \mathbf{1}_{\left\{g \geq A(d, \hat{d})\right\}} v(\theta, g + d) \tag{A.14}$$

$$s.t. \ g + d \leq \bar{\ell}(\theta),$$

$$d \in \{0, m\},$$

where

$$A\left(d, \hat{d}\right) = \Phi\left(\sqrt{\alpha_d}\left(\hat{d} - d\right)\right).$$

First, define $\tilde{\theta}$ as the solution to

$$m + A(m, \hat{d}) = \bar{\ell}(\tilde{\theta}), \tag{A.15}$$

θ_0 as the solution

$$m = \bar{\ell}(\theta_0), \tag{A.16}$$

θ_1 as the solution to

$$\lambda m + v\left(\theta_1, A(m, \hat{d}) + m\right) = v\left(\theta_1, A(0, \hat{d})\right), \tag{A.17}$$

and θ_2 as the solution to

$$A(0, \hat{d}) = \bar{\ell}(\theta_2). \tag{A.18}$$

First, notice that if $\hat{d} > 0$, assumption A1' ensures that $A(0, \hat{d}) > \frac{1}{2}$, so $m < \frac{1}{2}$ ensures that $A(0, \hat{d}) > m$. We, therefore, have two main cases to consider, the case where $A(0, \hat{d}) \geq A(m, \hat{d}) + m$ and $A(0, \hat{d}) < A(m, \hat{d}) + m$.

Consider first the case where $A(0, \hat{d}) \geq A(m, \hat{d}) + m$. We then have that $\theta_2 \geq \tilde{\theta} \geq \theta_0$. For $\theta \geq \theta_2$, banks in this range always survive since $A(0, \hat{d}) \leq \bar{\ell}(\theta)$. If $\lambda m + v\left(\theta, A(m, \hat{d}) + m\right) \geq v\left(\theta, A(0, \hat{d})\right)$ the bank sets $d = m$ and zero otherwise. Since $A(0, \hat{d}) \geq A(m, \hat{d}) + m$, the bank always pays dividends in this region. For $\theta \in [\tilde{\theta}, \theta_2)$ the bank survives if it pays dividends and fails if not. Since $v\left(\theta, A(m, \hat{d}) + m\right) > v\left(\theta, \bar{\ell}(\theta)\right) = 0$ the bank pays dividends $d = m$ and survive. For $\theta \in [\theta, \tilde{\theta})$ the bank always fail. Since $\bar{\ell}(\theta) \geq m$ for $\theta \in [\theta_0, \tilde{\theta})$, the bank sets $d = m$. For $\theta < \theta_0$ both paying dividends and surviving is not feasible and the bank fails with $d = 0$. Thus, if $A(0, \hat{d}) \geq A(m, \hat{d}) + m$, $\theta_f = \tilde{\theta}$ with $d = m$ if $\theta \in [\theta, \infty)$ and $d = 0$ otherwise.

Next, consider the case where $A(0, \hat{d}) < A(m, \hat{d}) + m$. We then have that $\tilde{\theta} \geq \theta_2 \geq \theta_0$. For $\theta \geq \tilde{\theta}$, the bank survives regardless. For $\theta \in [\theta_2, \tilde{\theta})$ the bank can pay dividends and fail or don't pay dividends and survive. We then have two subcases. If $\lambda m \geq v\left(\tilde{\theta}, A(0, \hat{d})\right)$ (Case 1') the bank pay dividends and fail. If $\lambda m < v\left(\tilde{\theta}, A(0, \hat{d})\right)$ (Case 2') the bank don't pay dividends and survive. If $\theta \in [\theta_0, \theta_2)$ dividends is feasible but survival without dividends is not, so the bank set $d = m$ and fail. If $\theta \in (-\infty, \theta_0)$ both dividends and survival is not feasible and the bank thus fails with $d = 0$. Thus, if we are in case 1', $\theta_f = \tilde{\theta}$. If we are in case 2', $\theta_f = \theta_a$, where θ_a solves $\lambda m = v\left(\theta_a, A(0, \hat{d})\right)$. Furthermore, in Case 1' $d = m$ for $\theta \in (\theta_0, \infty)$ and $d = 0$ otherwise. In Case 2', $d = m$ for

$\theta \in [\theta_0, \theta^f) \cup [\theta_1, \infty)$ and $d = 0$ otherwise. To see the latter, notice that from the properties of $v(\theta, l)$, $\theta_1 \geq \tilde{\theta}$ in this case since $v_\theta \left(\theta, A(m, \hat{d}) + m\right) - v_\theta \left(\theta, A(0, \hat{d})\right) > 0$ by the properties of $v(\theta, l)$ and from the fact that $A(m, \hat{d}) + m > A(0, \hat{d})$.

In either case,

$$g = \begin{cases} [0, \bar{\ell}(\theta) - d(\theta) & \theta \leq \theta_f \\ A(d, \hat{d}) & \theta > \theta_f \end{cases}. \tag{A.19}$$

Finally, notice that if $\theta_f = \tilde{\theta}$, applying the implicit function theorem on the failure condition $m + A(m, \hat{d}) - \bar{\ell}(\theta_f) = 0$ yields $\dfrac{\partial \theta_f}{\partial \hat{d}} = \dfrac{A_{\hat{d}}}{\bar{\ell}'(\theta_f)} > 0$. If $\theta_f = \theta_a$, applying the implicit function theorem on the failure condition $\lambda m - v\left(\theta_f, A(0, \hat{d})\right) = 0$ yields $\dfrac{\partial \theta_f}{\partial \hat{d}} = -\dfrac{v_l}{v_\theta} A_{\hat{d}} > 0$. $\qquad \square$

Next, we characterize the lenders' problem.

Lemma A.2. *(Strategic cutoff). Suppose that assumptions A2 and A3 hold, and let θ_f denote the bank failure threshold. If $\Theta_1 = [\theta_0, \infty)$, then there exists a unique strategic cutoff $\hat{d}(\theta_f)$, such that a lender runs iff $d_i \leq \hat{d}(\theta_f)$. Furthermore, $\hat{d}(\theta_f)$ satisfies*

$$\hat{d} = \frac{m}{2} + \frac{1}{\alpha_d m} \log \left(\frac{p \Pr \{\theta < \theta_0\}}{\Pr \{\theta > \theta_f\} - p \Pr \{\theta > \theta_0\}} \right). \tag{A.20}$$

If $\Theta_1 = [\theta_0, \theta_f] \cup [\theta_1, \infty)$ and $\Pr \{\theta < \underline{\theta}\} > 1 - p$, then there exists a unique strateigc cutoff $\hat{d}(\theta_f)$, such that a lender runs iff $d_i \leq h(\hat{d})$. Furthermore, $\hat{d}(\theta_f)$ satisfies

$$\hat{d} = \frac{m}{2} + \frac{1}{\alpha_d m} \log \left(\frac{p \Pr \{\theta < \theta_0\} - (1 - p) \Pr \{\theta \in (\theta_f, \theta_1)\}}{\Pr \{\theta > \theta_f\} - p \Pr \{\theta > \theta_0\} - (1 - p) \Pr \{\theta \in (\theta_f, \theta_1)\}} \right). \tag{A.21}$$

Proof. We first show that given Assumption A2, a higher dividend signal constitutes good news about bank survival. Let $\Theta_0 \subset \Theta$ denote the set of banks that choose $d(\theta) = 0$, and $\Theta_1 \subset \Theta$ denote the set of banks that choose $d(\theta) = m$. Then

$$\Pr \{\theta < y | d_i\}$$

is strictly decreasing in d_i, iff

$$\Pr \{\Theta_1 | \theta < y\} < \Pr \{\Theta_1\}. \tag{A.22}$$

To show this, from Bayes' rule, we have

$$\begin{aligned} \Pr \{\theta < y | d_i\} &= \frac{f(d_i | \theta < y) \Pr \{\theta < y\}}{f(d_i | \theta < y) \Pr \{\theta < y\} + f(d_i | \theta > y) \Pr \{\theta > y\}} \\ &= \frac{\int_{-\infty}^{y} f_d(d_i | \theta) f_p(\theta) \, d\theta}{\int_{-\infty}^{y} f_d(d_i | \theta) f_p(\theta) \, d\theta + \int_{y}^{\infty} f_d(d_i | \theta) f_p(\theta) \, d\theta}, \end{aligned}$$

where $f_p(\theta)$ denotes the pdf for the prior belief over θ and $f_d(d_i|\theta)$ is the conditional pdf of d_i given θ. Notice that $d_i|\theta \sim N\left(d(\theta), \alpha_d^{-1}\right)$. Therefore,

$$
\begin{aligned}
\int_{-\infty}^{y} f_d(d_i|\theta) f_p(\theta) d\theta &= \int_{(-\infty,y)\cap\Theta_0} \sqrt{\alpha_d}\phi\left(\sqrt{\alpha_d}\left(d_i - d^0\right)\right) f_p(\theta) d\theta \\
&+ \int_{(-\infty,y)\cap\Theta_1} \sqrt{\alpha_d}\phi\left(\sqrt{\alpha_d}\left(d_i - d^1\right)\right) f_p(\theta) d\theta \\
&= \sqrt{\alpha_d}\phi\left(\sqrt{\alpha_d}\left(d_i - d^0\right)\right) \Pr\{\{\theta < y\}\cap\Theta_0\} \\
&+ \sqrt{\alpha_d}\phi\left(\sqrt{\alpha_d}\left(d_i - d^1\right)\right) \Pr\{\{\theta < y\}\cap\Theta_1\},
\end{aligned}
$$

and analogously for $\int_y^{\infty} f_d(d_i|\theta) f_p(\theta) d\theta$. Simplifying, we get the following expression for $\Pr\{\theta < y|d_i\}$,

$$
\Pr\{\theta < y|d_i\} = \Pr\{\theta < y\} \frac{1 + (LR(d_i) - 1)\Pr\{\Theta_1|\theta < y\}}{1 + (LR(d_i) - 1)\Pr\{\Theta_1\}},
$$

where

$$
LR(x) \equiv \frac{f_d\left(x|d^1, \alpha_d\right)}{f_d\left(x|d^0, \alpha_d\right)} = \exp\left\{\alpha_d\left(d^1 - d^0\right)\left(x - \frac{d^1 + d^0}{2}\right)\right\}.
$$

Notice that $LR' > 0$, so higher realizations of d_i imply that it is more likely that it is drawn from a distribution with a mean of d^1. Thus,

$$
\begin{aligned}
\frac{\partial}{\partial d_i}\left(\Pr\{\theta < y|d_i\}\right) &= \Pr\{\theta < y\} LR' \frac{\Pr\{\Theta_1|\theta < y\} - \Pr\{\Theta_1\}}{\left(1 + [LR(d_i) - 1]\Pr\{\Theta_1\}\right)^2} < 0 \\
&\iff \Pr\{\Theta_1|\theta < y\} < \Pr\{\Theta_1\}.
\end{aligned}
$$

Therefore, for $y = \theta_f$, we have that

$$
\Pr\{\Theta_1|\theta < \theta_f\} = \frac{\Pr\{\theta \in (\underline{\theta}, \theta_f)\}}{\Pr\{\theta < \underline{\theta}\} + \Pr\{\theta \in (\underline{\theta}, \theta_f)\}} < \frac{\Pr\{\theta \in (\underline{\theta}, \overline{\theta})\}}{\Pr\{\theta < \underline{\theta}\}},
$$

since banks in the lower-domiance region never pay a dividend. Furthermore, since banks in the upper dominance region always pay a dividend, it follows that

$$
\Pr\{\Theta_1\} > \Pr\{\theta > \overline{\theta}\}.
$$

Therefore,

$$
\Pr\{\Theta_1|\theta < \theta_f\} < \frac{\Pr\{\theta \in (\underline{\theta}, \overline{\theta})\}}{\Pr\{\theta < \underline{\theta}\}} < \Pr\{\theta > \overline{\theta}\} < \Pr\{\Theta_1\},
$$

where the second inequality follows by Assumption A2.

Therefore, given a failure threshold $\theta_f \in \left[\underline{\theta}, \overline{\theta}\right]$, the expected net payoff of an agent i with signal d_i is given by

$$\hat{\pi}_i(d_i, \theta_f) = p - \Pr\{g > A|d_i\}$$
$$= p - \Pr\{\theta > \theta_f|d_i\}$$
$$= p - 1 + \Pr\{\theta < \theta_f|d_i\}.$$

So,

$$\hat{\pi}(d_i, \theta_f) = p - 1 + \Pr\{\theta \leq \theta_f\} \frac{1 + (LR(d_i) - 1)\Pr\{\Theta_1|\theta \leq \theta_f\}}{1 + (LR(d_i) - 1)\Pr\{\Theta_1\}}. \tag{A.23}$$

By the above discussion, we have that $\dfrac{\partial \hat{\pi}(d_i, \theta_f)}{\partial d_i} < 0$.

Next, we proceed to characterize the signal $\hat{d}$ which makes a lender indifferent between rolling over the debt and running satisfies

$$\hat{\pi}(\hat{d}, \theta_f) = 0. \tag{A.24}$$

Since $\dfrac{\partial \hat{\pi}(d_i, \theta_f)}{\partial d_i} < 0$ and $\hat{\pi}(d_i, \theta_f)$ is continuous, a threshold signal $\hat{d}$ such that an agent runs iff $d_i \leq \hat{d}$ exists and is unique if $\lim_{d_i \to -\infty} \hat{\pi}(d_i, \theta_f) > 0$ and $\lim_{d_i \to \infty} \hat{\pi}(d_i, \theta_f) < 0$. To see that this is indeed the case, observe that $\lim_{d_i \to \infty} LR(d_i) = \infty$ and $\lim_{d_i \to -\infty} LR(d_i) = 0$. We then have that

$$\lim_{d_i \to -\infty} \hat{\pi}(d_i, \theta_f) = p - 1 + \Pr\{\theta \leq \theta_f\} \frac{1 - \Pr\{\Theta_1|\theta \leq \theta_f\}}{1 - \Pr\{\Theta_1\}}. \tag{A.25}$$

From Lemma A.1, we can either have that $\Theta_1 = [\theta_0, \infty)$ with $\theta_f = \tilde{\theta}$ or $\Theta_1 = [\theta_0, \theta_f) \cup [\theta_1, \infty)$ with $\theta_f = \theta_a$.

If $\Theta_1 = [\theta_0, \infty)$, then

$$\lim_{d_i \to -\infty} \hat{\pi}(d_i, \theta_f) = p - 1 + 1 = p > 0. \tag{A.26}$$

If $\Theta_1 = [\theta_0, \theta_f) \cup [\theta_1, \infty)$, then

$$\lim_{d_i \to -\infty} \hat{\pi}(d_i, \theta_f) = p - 1 + \frac{\Pr\{\theta < \theta_0\}}{\Pr\{\theta < \theta_0\} + \Pr\{\theta \in (\theta_f, \theta_1)\}}. \tag{A.27}$$

Notice that $\Pr\{\theta < \theta_0\} + \Pr\{\theta \in (\theta^f, \theta_1)\} < 1$. Also, if $\Pr\{\theta < \underline{\theta}\} > 1 - p$ then $\Pr\{\theta < \theta_0\} > 1 - p$. Therefore, $\lim_{d_i \to -\infty} \hat{\pi}(d_i, \theta_f) > 0$. Thus, in both cases $\lim_{d_i \to -\infty} \hat{\pi}(d_i, \theta_f) > 0$.

Similarly, we have that when $\Theta_1 = [\theta_0, \infty)$

$$\lim_{d_i \to \infty} \hat{\pi}(d_i, \theta_f) = p - 1 + \frac{\Pr\{\theta < \theta_f\} - \Pr\{\theta < \theta_0\}}{1 - \Pr\{\theta < \theta_0\}}, \tag{A.28}$$

and when $\Theta_1 = [\theta_0, \theta_f) \cup [\theta_1, \infty)$

$$\lim_{d_i \to \infty} \hat{\pi}(d_i, \theta_f) = p - 1 + \frac{\Pr\{\theta < \theta_f\} - \Pr\{\theta < \theta_0\}}{\Pr\{\theta < \theta_f\} + \Pr\{\theta > \theta_1\} - \Pr\{\theta < \theta_0\}}. \tag{A.29}$$

Again, $\Pr\{\theta < \theta_f\} + \Pr\{\theta > \theta_1\} < 1$. Thus, if we can show that $\lim_{d_i \to \infty} \hat{\pi}(d_i, \theta_f) < 0$ for $\Theta_1 = [\theta_0, \theta^f) \cup [\theta_1, \infty)$, it must also be so for $\Theta_1 = [\theta_0, \infty)$.

We can write

$$
\begin{aligned}
\lim_{d_i \to \infty} \hat{\pi}(d_i, \theta_f) &= p - 1 + \frac{\Pr\{\theta < \theta_f\} - \Pr\{\theta < \theta_0\}}{\Pr\{\theta < \theta_f\} + \Pr\{\theta > \theta_1\} - \Pr\{\theta < \theta_0\}} \\
&= p - 1 + \frac{\Pr\{\theta < \theta_f\} - \Pr\{\theta < \theta_0\}}{1 - \Pr\{\theta < \theta_0\} - \Pr\{\theta \in (\theta_f, \theta_1)\}} \\
&= p - \frac{1 - \Pr\{\theta < \theta_f\} - \Pr\{\theta \in (\theta_f, \theta_1)\}}{1 - \Pr\{\theta < \theta_0\} - \Pr\{\theta \in (\theta_f, \theta_1)\}},
\end{aligned}
$$

so

$$
\lim_{d_i \to \infty} \hat{\pi}(d_i, \theta_f) < 0 \Leftrightarrow p \le \frac{\Pr\{\theta > \theta_f\} - \Pr\{\theta \in (\theta_f, \theta_1)\}}{\Pr\{\theta > \theta_0\} - \Pr\{\theta \in (\theta_f, \theta_1)\}}. \tag{A.30}
$$

By assumption A2, $p < \frac{\Pr\{\theta > \bar{\theta}\}}{\Pr\{\theta > \theta_0\}}$. Notice also that $\Pr\{\theta > \theta_f\} \ge \Pr\{\theta > \bar{\theta}\}$, so $p < \frac{\Pr\{\theta > \theta_f\} - \Pr\{\theta \in (\theta_f, \theta_1)\}}{\Pr\{\theta > \theta_0\} - \Pr\{\theta \in (\theta_f, \theta_1)\}}$ Thus, $\lim_{d_i \to \infty} \hat{\pi}(d_i, \theta_f) < 0$ in both cases and that there exists a unique $\hat{d}(\theta_f)$ such that $\hat{\pi}(\hat{d}, \theta_f) = 0$.

Finally, to characterize the strategic cutoff, notice that $\hat{\pi}(d_i, \theta_f) = 0$ can be written as

$$
p - 1 + \Pr\{\theta \le \theta_f\} \frac{1 + \left(LR\left(\hat{d}\right) - 1\right) \Pr\{\Theta_1 | \theta \le \theta_f\}}{1 + \left(LR\left(\hat{d}\right) - 1\right) \Pr\{\Theta_1\}} = 0. \tag{A.31}
$$

When $\Theta_1 = [\theta_0, \infty)$, we have that $\Pr\{\Theta_1 | \theta \le \theta_f\} = \Pr\{\theta < \theta_f\} - \Pr\{\theta < \theta_0\}$, $\Pr\{\Theta_1\} = \Pr\{\theta > \theta_0\}$ and thus solving for $\hat{d}$ yields

$$
\hat{d} = \frac{m}{2} + \frac{1}{\alpha_d m} \log\left(\frac{p \Pr\{\theta < \theta_0\}}{\Pr\{\theta > \theta_f\} - p \Pr\{\theta > \theta_0\}}\right). \tag{A.32}
$$

When $\Theta_1 = [\theta_0, \theta_f) \cup [\theta_1, \infty)$ we have that $\Pr\{\Theta_1 | \theta \le \theta_f\} = \Pr\{\theta < \theta_f\} - \Pr\{\theta < \theta_0\}$, $\Pr\{\Theta_1\} = \Pr\{\theta < \theta_f\} - \Pr\{\theta < \theta_0\} + \Pr\{\theta > \theta_1\}$ and thus solving for $\hat{d}$ yields

$$
\hat{d} = \frac{m}{2} + \frac{1}{\alpha_d m} \log\left(\frac{p \Pr\{\theta < \theta_0\} - (1 - p) \Pr\{\theta \in (\theta_f, \theta_1)\}}{\Pr\{\theta > \theta_f\} - p \Pr\{\theta > \theta_0\} - (1 - p) \Pr\{\theta \in (\theta_f, \theta_1)\}}\right). \tag{A.33}
$$

$\square$

Lemma A.2 shows that for a given θ_f and with dividend policies as either one of the two different policy profiles in Lemma A.1, there exists a unique dividend signal at which a lender is indifferent between running and rolling over.[2] When α_d is large, an agent knows with certainty that the bank's dividend policy is 0 if she observes a signal close to 0. If $\Theta_1 = [\theta_0, \infty)$, she would refuse to roll over, since banks paying $d = 0$ always fail. Alternatively, if she observes a signal close to m, she knows for sure that the bank dividend policy is m. In that case, the dividend policy can come from both

---

[2]The condition $\Pr\{\theta < \underline{\theta}\} > 1 - p$ in Lemma A.2 puts a lower bound on how pessimistic agents can be in terms of the probability of the run succeeding.

a failing and a surviving bank. Given that $p < \dfrac{\Pr\left\{\theta > \overline{\theta}\right\}}{\Pr\left\{\theta > \theta_0\right\}}$, she believes that the mass of surviving banks relative to all banks paying m is relatively large. Thus, she is better off rolling over in this case.

A.2 Omitted proofs

Proofs of results in Section 2.2

Proof of Proposition 2.1.

The bank-owner solves

$$\tilde{W}(\theta) = \max_{d \in [0, \ell(\theta)]} \left\{\lambda d + v(\theta, d)\right\}.$$

Taking the f.o.c. with respect to d, the optimal d^* solves

$$\lambda \leq -v_l(\theta, d^*) + \kappa_{\bar{l}},$$

where $\kappa_{\bar{l}}$ and d^* satisfy the complementary slackness condition $\kappa_{\bar{l}}\left(\bar{\ell}(\theta) - d^*\right) = 0$. Therefore, d^* satisfies

$$\left[\lambda + v_l(\theta, d^*)\right]\left(\bar{\ell}(\theta) - d^*\right)d^* = 0, \tag{A.34}$$

Let

$$\varphi(\theta) \equiv \lambda\bar{\ell}(\theta) - \tilde{W}(\theta).$$

Given Assumption B1, $\varphi(\theta)$ is (weakly) decreasing in θ. To show this, note first that $\tilde{W}(\theta) \geq \lambda\bar{\ell}(\theta)$ with equality, whenever $d^* = \bar{\ell}(\theta)$, so $\varphi(\theta) \leq 0$. By the theorem of the maximum, $\tilde{W}(\theta)$ is continuous in θ, so $\varphi(\theta)$ is also continuous in θ. Also, d^* is continuous in θ. Therefore, there are intervals of $\{\theta \geq \underline{\theta}\}$, where d^* may be on the lower boundary, interior or upper boundary of the feasible set. Denote those by Θ_L, Θ_I, Θ_U, respectively. For $\theta \in \Theta_U$, $\varphi(\theta) = 0$. For $\theta \in \Theta_L$, $\varphi(\theta) = \lambda\bar{\ell}(\theta) - v(\theta, 0)$, so $\varphi'(\theta) = \lambda\bar{\ell}'(\theta) - v_\theta(\theta, 0)$. Similarly, for $\theta \in \Theta_I$, applying the envelope theorem, we get

$$\varphi'(\theta) = \lambda\bar{\ell}'(\theta) - v_\theta(\theta, d^*). \tag{A.35}$$

Suppose, toward a contradiction, that $\varphi(\theta)$ is strictly increasing in θ, for some θ_0. Since, $\varphi(\theta) = 0$ for $\theta \in \Theta_U$, it follows that $\theta_0 \in \Theta_L \cup \Theta_I$, and so

$$\varphi'(\theta_0) = \lambda\bar{\ell}'(\theta_0) - v_\theta(\theta_0, d^*(\theta_0)). \tag{A.36}$$

Noting that $\overline{\ell}' = -\frac{v_\theta(\theta_0, \overline{\ell}(\theta_0))}{v_l(\theta_0, \overline{\ell}(\theta_0))}$ and using the first-order condition for d^* at θ_0, $\lambda \leq -v_l(\theta_0, d^*(\theta_0))$, we get that

$$\varphi'(\theta_0) \quad \leq \quad v_l(\theta_0, d^*(\theta_0)) \frac{v_\theta(\theta_0, \overline{\ell}(\theta_0))}{v_l(\theta_0, \overline{\ell}(\theta_0))} - v_\theta(\theta_0, d^*(\theta_0)) \tag{A.37}$$

$$= \quad v_l(\theta_0, d^*(\theta_0)) \left(\frac{v_\theta(\theta_0, \overline{\ell}(\theta_0))}{v_l(\theta_0, \overline{\ell}(\theta_0))} - \frac{v_\theta(\theta_0, d^*(\theta_0))}{v_l(\theta_0, d^*(\theta_0))} \right) < 0, \tag{A.38}$$

where the last inequality comes from Assumption B1 and from $v_l < 0$. Thus, we reach a contradiction.

Therefore, by this property of $\varphi(\theta)$, if $\lambda < -v_l(\underline{\theta}, 0)$, then $\varphi(\theta) < 0$, for $\theta > \underline{\theta}$, and so, $d^*(\theta) < \overline{\ell}(\theta)$, for $\theta > \underline{\theta}$, with $d^*(\theta)$ determined by (2.9). Furthermore, $v_{l\theta} > 0$, implies that d^* is increasing in θ. To show this, note that for $\theta \in \Theta_I$, $\frac{\partial d^*}{\partial \theta} = -\frac{v_{l\theta}}{v_{ll}} > 0$, and since d^* is continuous in θ, it follows that for any $\theta_U \in \Theta_U$, for which $d^* = 0$, $\theta_U \leq \theta$, $\forall \theta \in \Theta_I$.

Similarly, if $\lambda \geq -v_l(\underline{\theta}, 0)$, then a non-increasing $\varphi(\theta)$ implies that there is a unique critical value of θ, θ^*, such that for a bank with $\theta \leq \theta^*$, $d^* = \overline{\ell}(\theta)$ and for a bank with $\theta > \theta^*$, $d^* < \overline{\ell}(\theta)$. Furthermore, $v_{l\theta} > 0$, and continuity of d^* imply that $d^* > 0$ for $\theta > \theta^*$. To show this, note that for $\theta \in \Theta_I$, $\frac{\partial d^*}{\partial \theta} = -\frac{v_{l\theta}}{v_{ll}} > 0$, and since $d^* > 0$, for $\theta \leq \theta^*$ and is continuous, there can be no value of $\theta > \theta^*$, for which $d^* = 0$. Finally, d^* is increasing in θ, since $\frac{\partial d^*}{\partial \theta} = \overline{\ell}'(\theta)$, for $\theta < \theta^*$. Finally, notice that continuity of d^* implies that θ^* must solve

$$\lambda = -v_l(\theta^*, \overline{\ell}(\theta^*)). \tag{A.39}$$

$\square$

Proofs of results in Section 2.3

Proof of Proposition 2.2.

We show this proposition in three Lemmas. First, we show that for α_d sufficiently large, it is always the case that $\lambda m \geq v\left(\overline{\ell}^{-1}\left(m + A\left(m, \hat{d}\right)\right), A(0, \hat{d})\right)$. Next, we show that there is a unique equilibrium in monotone strategies. Finally, we show that that equilibrium is the unique equilibrium of this economy.

Lemma A.3. *There is an $\overline{\alpha}_1 > 0$, such that for $\alpha_d > \overline{\alpha}_1$, $\lambda m \geq v\left(\overline{\ell}^{-1}\left(m + A\left(m, \hat{d}\right)\right), A(0, \hat{d})\right)$.*

Proof. Notice that an equilibrium value of $\hat{d}$ always have to satisfy either

$$\hat{d} = \frac{m}{2} + \frac{1}{\alpha_d m} \log\left(\frac{p \Pr\{\theta < \theta_0\}}{\Pr\{\theta > \theta_f\} - p \Pr\{\theta > \theta_0\}} \right)$$

or

$$\hat{d} = \frac{m}{2} + \frac{1}{\alpha_d m} \log\left(\frac{p \Pr\{\theta < \theta_0\} - (1-p) \Pr\{\theta \in (\theta_f, \theta_1)\}}{\Pr\{\theta > \theta_f\} - p \Pr\{\theta > \theta_0\} - (1-p) \Pr\{\theta \in (\theta^f, \theta_1)\}} \right)$$

depending on whether we are in Case 1' with $\Theta_1 = [\theta_0, \infty)$ and $\theta_f = \tilde{\theta}$ or in Case 2' with $\Theta_1 = [\theta_0, \theta_f) \cup [\theta_1, \infty)$ and $\theta_f = \theta_a$. Thus, in both cases $\hat{d}$ is a continuous function of α_d. Furthermore, $\lim_{\alpha_d \to \infty} \hat{d} = \dfrac{m}{2}$ in both cases. Since $\hat{d}$ is continuous in α_d, this means that $\hat{d}$ can be made arbitrarily close to $\frac{m}{2}$ for sufficiently high values of α_d and for any $\theta_f \in (\underline{\theta}, \overline{\theta})$. However, as $\hat{d} \to \frac{m}{2}$, $v\left(\overline{\ell}^{-1}\left(m + A\left(m, \hat{d}\right)\right), A\left(0, \hat{d}\right)\right) \to v\left(\overline{\ell}^{-1}(m), 1\right) = 0$ for $\theta \in (\underline{\theta}, \overline{\theta})$ and, thus, $\lambda m \geq v\left(\overline{\ell}^{-1}\left(m + A\left(m, \hat{d}\right)\right), A\left(0, \hat{d}\right)\right)$. Therefore, there is a $\overline{\alpha}_1 > 0$, such that for $\alpha_d > \overline{\alpha}_1$. $\quad\square$

Lemma A.4. *There is an $\overline{\alpha}$, such that for $\alpha_d > \overline{\alpha}$, there is a unique monotone strategy equilibrium, in which $\hat{d}$, and θ_f are uniquely determined by conditions (2.16) and (2.17) and a bank pays a dividend iff $\theta \geq \theta_0$.*

Proof. From Lemma A.1, we have that $\dfrac{\partial \theta_f}{\partial \hat{d}} > 0$. Hence, the expected net payoff from attacking $\hat{\pi}(d_i, \theta_f)$ is an increasing function of the strategic cutoff. Given that all other lenders follow a strategy $\hat{d}$ denote $h(\hat{d})$ as the solution to

$$\hat{\pi}\left(h(\hat{d}), \theta_f\left(\hat{d}\right)\right) = 0. \tag{A.40}$$

By the properties of $\hat{\pi}$ and the implicit function theorem, $h(\hat{d})$ is increasing in $\hat{d}$. To show that there exists a unique equilibrium in monotone strategies, we show that $h(\hat{d})$ has a unique fixed point $\hat{d} = h(\hat{d})$. To show this, it is sufficient to show that $h'\left(\hat{d}\right) \in [0, 1)$, so that that h is a contraction mapping. Let f_p denote the pdf of the lenders' prior belief. Furthermore, suppose that $\alpha_d > \overline{\alpha}_1$. In that case, we are in Case 1'. Then, applying the implicit function theorem on equation A.24 yields

$$h'\left(\hat{d}\right) = \frac{1}{\alpha_d m} \frac{1}{p \Pr\{\theta < \theta_0\} + 1 - \Pr\{\theta \leq \theta_f\} - p} f_p(\theta_f) \frac{\partial \theta_f}{\partial \hat{d}}. \tag{A.41}$$

We then have that $h'\left(\hat{d}\right) \geq 0 \Leftrightarrow p \Pr\{\theta < \theta_0\} + 1 - \Pr\{\theta \leq \theta_f\} - p > 0$. Assumption A2 ensures that this is the case.

To show that $h'\left(\hat{d}\right) < 1$, first note that

$$
\begin{aligned}
\frac{\partial \theta_f}{\partial \hat{d}} &= -A_{\hat{d}} \frac{v_l}{v_\theta}\big|_{\tilde{\theta}} \\
&= -\sqrt{\alpha_d}\phi_d\left(\sqrt{\alpha_d}(\hat{d} - m)\right)\left(\overline{\ell}^{-1}\left(m + A\left(m, \hat{d}\right)\right)\right)',
\end{aligned}
$$

so

$$h'\left(\hat{d}\right) < 1 \Leftrightarrow -\sqrt{\frac{1}{\alpha_d}} \frac{1}{m} \frac{f_p(\theta_f)\phi_d\left(\sqrt{\alpha_d}(\hat{d} - m)\right)}{p \Pr\{\theta < \theta_0\} + 1 - \Pr\{\theta \leq \theta_f\} - p} \left(\overline{\ell}^{-1}\left(m + A\left(m, \hat{d}\right)\right)\right)' < 1. \tag{A.42}$$

Noting that $\hat{d} \to \frac{m}{2}$ as $\alpha_d \to \infty$, it follows that $\phi_d\left(\sqrt{\alpha_d}(\hat{d} - m)\right) \to 0$ as $\alpha_d \to \infty$. Hence, there exists a $\overline{\alpha}_2$, such that for $\alpha_d > \overline{\alpha}_2$, the inequality holds. Then defining $\overline{\alpha} = \min\{\overline{\alpha}_1, \overline{\alpha}_2\}$, we can

conclude that for $\alpha_d > \overline{\alpha}$, $h(\cdot)$ has a unique fixed point $\hat{d} = h(\hat{d})$. This is the unique equilibrium in monotone strategies. $\qquad\square$

Lemma A.5. *There is an $\overline{\alpha}$, such that for $\alpha_d > \overline{\alpha}$, the unique monotone strategy equilibrium of this economy is also the unique equilibrium.*

Proof. We take $\overline{\alpha}$ to be the value from Lemma A.4. If $\alpha_d > \overline{\alpha}$, we are always in Case 1' for all equilibrium values of $\hat{d}$ and θ_f. Furthermore, $\left(\hat{d}, \theta_f\right)$ is the unique equilibrium in monotone strategies.

Let us first establish that there exists a pair $\underline{\hat{d}} < \overline{\hat{d}}$ such that attacking is strictly dominant for all $d_i \leq \underline{\hat{d}}$ and not attacking is strictly dominant for $d_i \geq \overline{\hat{d}}$. Consider $\underline{\hat{d}}$ first. The most pessimistic scenario an agent can consider is that $\theta_f = \underline{\theta}$. With this belief, the strategic threshold for an agent is pinned down by the condition

$$\Pr\left\{\theta < \underline{\theta}|\underline{\hat{d}}\right\} = 1 - p. \tag{A.43}$$

Notice that in this case

$$\Pr\left\{\theta < \underline{\theta}|\underline{\hat{d}}\right\} = \Pr\left\{\theta < \underline{\theta}\right\} \frac{1}{1 + \left(LR(\underline{\hat{d}}) - 1\right)\Pr\left\{\Theta_1\right\}}, \tag{A.44}$$

since $\Pr\left\{\Theta_1|\theta < \underline{\theta}\right\} = 0$. $\Pr\left\{\theta < \underline{\theta}|\underline{\hat{d}}\right\}$ is a continuous and strictly decreasing function of $\underline{\hat{d}}$ with $\lim_{\underline{\hat{d}} \to -\infty} \Pr\left\{\theta < \underline{\theta}|\underline{\hat{d}}\right\} = \frac{\Pr\left\{\theta < \underline{\theta}\right\}}{\Pr\left\{\theta \leq \theta_0\right\}} > 1 - p$ and $\lim_{\underline{\hat{d}} \to \infty} \Pr\left\{\theta < \underline{\theta}|\underline{\hat{d}}\right\} = 0$. Thus, by Bolzano's theorem there is a unique $\underline{\hat{d}}$ such that $\Pr\left\{\theta < \underline{\theta}|\underline{\hat{d}}\right\} = 1 - p$. A similar argument, where the most optimistic belief is that $\theta_f = \overline{\theta}$, establishes $\overline{\hat{d}}$.

Next, let's set $\underline{\hat{d}}_0 = \underline{\hat{d}}$. It is strictly dominant to refuse to rollover if $d_i < \underline{\hat{d}}_0$. But if all agents follow a strategy $\underline{\hat{d}}_0$, it is strictly dominant to attack for $d_i < h(\underline{\hat{d}}_0)$. Similarly, set $\overline{\hat{d}}_0 = \overline{\hat{d}}$. If it is strictly dominant to not attack for $d_i < \overline{\hat{d}}_0$. But if all agents follow a strategy $\overline{\hat{d}}_0$, it is strictly dominant to not attack for $d_i < h(\overline{\hat{d}}_0)$.

Therefore, we can construct two monotone sequences, with $\{\underline{\hat{d}}_n\}_{n=0}^{\infty}$ and $\{\overline{\hat{d}}_n\}_{n=0}^{\infty}$ where $\underline{\hat{d}}_{n+1} = h(\underline{\hat{d}}_n)$ and $\overline{\hat{d}}_{n+1} = h(\overline{\hat{d}}_n)$. $\{\underline{\hat{d}}_n\}_{n=0}^{\infty}$ is bounded above by a $\hat{d}^*$ and $\{\overline{\hat{d}}_n\}_{n=0}^{\infty}$ is bounded below by the same $\hat{d}^*$. Thus, by the discussion above, both these sequences converge to the same fixed point $\hat{d}^*$ as $n \to \infty$. $\qquad\square$

Proof of Proposition 2.3.

Suppose that $\alpha_d > \overline{\alpha}$. In that case, θ_f is implicitly defined by $\overline{\ell}(\theta_f) = m + A\left(m, \hat{d}\right)$ and with $\hat{d}(\theta_f; \alpha_d) = \frac{m}{2} + \frac{1}{\alpha_d m}\log\left(\frac{p\Pr\{\theta < \theta_0\}}{p\Pr\{\theta < \theta_0\} + \Pr\{\theta > \theta_f\} - p}\right)$. Since $A(m, \hat{d}) = \Phi\left(\sqrt{\alpha_d}\left(\hat{d} - m\right)\right)$, we can write $\overline{\ell}(\theta_f) = m + A\left(m, \hat{d}\left(\theta_f, \alpha_d\right); \alpha_d\right)$.

Then, by the implicit function theorem

$$\frac{\partial \theta_f}{\partial \alpha_d} = -\frac{-A_{\hat{d}}\frac{\partial \hat{d}}{\partial \alpha_d} - A_\alpha}{\bar{\ell}'\left(\theta_f\right) - A_{\hat{d}}\frac{\partial \hat{d}}{\partial \theta_f}} \tag{A.45}$$

We have that $A_{\hat{d}} = \phi\left(\sqrt{\alpha_d}\left(\hat{d} - m\right)\right)\sqrt{\alpha_d}$ and $A_\alpha = \phi\left(\sqrt{\alpha_d}\left(\hat{d} - m\right)\right)\frac{1}{\sqrt{\alpha_d}}\left(\hat{d} - m\right)$. Furthermore

$$\frac{\partial \hat{d}}{\partial \alpha_d} = -\frac{1}{\alpha_d^2 m} \log\left(\frac{p\Pr\{\theta < \theta_0\}}{\Pr\{\theta > \theta^f\} - p\Pr\{\theta > \theta_0\}}\right) \tag{A.46}$$

and

$$\frac{\partial \hat{d}}{\partial \theta^f} = -\frac{1}{\alpha_d m}\frac{1}{\Pr\{\theta > \theta^f\} - p\Pr\{\theta > \theta_0\}}\frac{\partial \Pr\{\theta > \theta^f\}}{\partial \theta^f} \tag{A.47}$$

Inserting the partial derivatives into equation A.45 and rearranging gives

$$\frac{\partial \theta_f}{\partial \alpha_d} = \frac{-\phi\left(\cdot\right)\frac{1}{\alpha^{3/2}}\log\left(\frac{p\Pr\{\theta < \theta_0\}}{\Pr\{\theta > \theta_f\} - p\Pr\{\theta > \theta_0\}}\right) + \phi\left(\cdot\right)\frac{1}{2}\frac{1}{\sqrt{\alpha_d}}\left(\hat{d} - m\right)}{\ell'\left(\theta_f\right) + \phi\left(\cdot\right)\frac{1}{\sqrt{\alpha_d}m}\frac{1}{\Pr\{\theta > \theta_f\} - p\Pr\{\theta > \theta_0\}}\frac{\partial \Pr\{\theta > \theta_f\}}{\partial \theta_f}} \tag{A.48}$$

where $\phi\left(\cdot\right) = \phi\left(\sqrt{\alpha_d}\left(\hat{d} - m\right)\right)$. Notice that, for an α_d sufficiently large, the denominator is positive. In that case,

$$\frac{\partial \theta_f}{\partial \alpha_d} \leq 0 \quad \Leftrightarrow \quad -\frac{1}{\alpha_d}\log\left(\frac{p\Pr\{\theta < \theta_0\}}{\Pr\{\theta > \theta_f\} - p\Pr\{\theta > \theta_0\}}\right) + \frac{1}{2}\left(\hat{d} - m\right) \leq 0$$

Since $\hat{d} \to \frac{m}{2}$, this condition holds for an α_d sufficiently large. $\qquad\square$

Proof of Proposition 2.4.

First, notice that if $p < 1$, $\hat{d}$ given by

$$\hat{d} = \frac{m}{2} + \frac{1}{\alpha_d m}\log\left(\frac{p\Pr\{\theta < \theta_0\}}{p\Pr\{\theta < \theta_0\} + \Pr\{\theta > \theta_f\} - p}\right). \tag{A.49}$$

is well-defined, if $\theta_f = \theta_0$. Furthermore as $\alpha_d \to \infty$, $\hat{d} \to \frac{m}{2}$ and we are in Case 1' by Lemma A.3. Turning to the share of lenders that run in the limit, using $\hat{d} \to \frac{m}{2}$, we have that $A\left(0, \hat{d}\right) \to 1$ and $A\left(m, \hat{d}\right) \to 1$. Therefore, in the limit, θ_f satisfies

$$\bar{\ell}\left(\lim_{\alpha_d \to \infty} \theta_f\right) = m + \lim_{\alpha_d \to \infty} A\left(m, \hat{d}\right) = m, \tag{A.50}$$

which is precisely the condition that defines θ_0. Finally, to verify the conjecture that the economy is in Case 1', notice that given $m < \frac{1}{2}$, at $\theta = \theta_0$, a bank cannot survive to a run of size 1, which will be the case if it were to set $d = 0$. Therefore,

$$\lambda m > v\left(\theta_0, A\left(0, \hat{d}\right)\right),\tag{A.51}$$

verifying the condition for the economy to be in Case 1'. $\hfill\square$

Proofs of results in Section 2.4

Proof of Lemma 2.1.

The bank-owner solves

$$W(\theta) = \max_{d \in \left[0, \bar{\ell}(\theta)\right]} \left\{\lambda d + \mathbf{1}_{\left\{d + A(d,\hat{d}) \leq \bar{\ell}(\theta)\right\}} v\left(\theta, d + A\left(d, \hat{d}\right)\right)\right\}.$$

Let $d_{nr}^*(\theta)$ and $\tilde{W}_{nr}(\theta)$ denote that optimal dividend policy and value function for a bank that faces no run. Also, let θ_{nr}^* denote that value of θ for which $d_{nr}^*(\theta) = \bar{\ell}(\theta)$ (see Lemma 2.1). Additionally, let us define $\mathcal{D}\left(\theta, \hat{d}\right) = \left\{d : d \geq 0, \ d + A(d,\hat{d}) \leq \bar{\ell}(\theta)\right\} \subset \left[0, \bar{\ell}(\theta)\right]$. Given the properties of $\bar{\ell}(\theta)$, $\mathcal{D}\left(\theta_1, \hat{d}\right) \subset \mathcal{D}\left(\theta_2, \hat{d}\right)$, $\forall \theta_1 < \theta_2$. Since $d_{\min}$ is the global minimizer of $d + A\left(d, \hat{d}\right)$, it follows that

$$\mathcal{D}\left(\theta, \hat{d}\right) = \begin{cases} \emptyset & , \ \theta < \theta_0 \\ \left[d_{\min}, \bar{d}\left(\theta\right)\right] & , \ \theta \geq \theta_0 \end{cases},\tag{A.52}$$

where $\bar{d}(\theta) > d_{\min}$ solves $\bar{d}(\theta) + A(\bar{d}(\theta), \hat{d}) = \bar{\ell}(\theta)$, and θ_0 solves

$$\bar{\ell}(\theta_0) = d_{\min} + A\left(d_{\min}, \hat{d}\right).\tag{A.53}$$

If $\mathcal{D}\left(\theta, \hat{d}\right) = \emptyset$, then the bank cannot meet the withdrawals of lenders. In that case it is optimal for the bank to set $d = \bar{\ell}(\theta)$ and $g = 0$, the bank-owner obtains $\tilde{W}(\theta) = \lambda \bar{l}(\theta)$, and the bank fails. If $\mathcal{D}\left(\theta, \hat{d}\right) \neq \emptyset$, then the bank can choose between:
 - Setting $d = \bar{l}(\theta)$ and obtaining $\tilde{W}(\theta) = \lambda \bar{\ell}(\theta)$
 - Solving

$$\max_{d \in \left[d_{\min}, \bar{d}(\theta)\right]} \lambda d + v\left(\theta, d + A(d, \hat{d})\right).\tag{A.54}$$

Taking the f.o.c. with respect to d, the optimal d^* satisfies

$$\lambda \leq -v_l\left(\theta, d^* + A\left(d^*, \hat{d}\right)\right)\left(1 + A_d\left(d^*, \hat{d}\right)\right) + \kappa_{\bar{l}}$$

where $\kappa_{\bar{l}}$ and d^* satisfy the complementary slackness condition $\kappa_{\bar{l}}\left(\bar{l}\left(\theta\right) - d^* - A(d^*, \hat{d})\right) = 0$.[3] Notice, however, that whenever, $d^* + A(d^*, \hat{d}) = \bar{l}\left(\theta\right)$, the bank is better off setting $d = \bar{l}\left(\theta\right)$ and $g = 0$, so one can disregard this case. Similarly, $d^* = d_{\min}$ only if $\bar{l}\left(\theta\right) = d_{\min}$ but in that case the bank is better off setting $d = \bar{l}\left(\theta\right)$ and $g = 0$ as well.

For a value of $d^* > d_{\min}$ that satisfies

$$\lambda + v_l\left(\theta, d^* + A\left(d^*, \hat{d}\right)\right)\left(1 + A_d\left(d^*, \hat{d}\right)\right) = 0, \tag{A.56}$$

the bank owner compares

$$\lambda\bar{l}\left(\theta\right) \gtrless \lambda d^* + v\left(\theta, d^* + A(d^*, \hat{d})\right). \tag{A.57}$$

Whenever the left-hand side is higher than the right-hand side, the bank sets $d = \bar{l}\left(\theta\right)$ and $g = 0$. Otherwise, it sets $d = d^*$ and $g = A\left(d^*, \hat{d}\right)$.

Next, define

$$\varphi\left(\theta\right) \equiv \lambda\bar{l}\left(\theta\right) - \lambda d^* - v\left(\theta, d^* + A\left(\theta, \hat{\theta}\right)\right), \tag{A.58}$$

for $\theta \geq \theta_0$, where d^* solves (A.56), and let $\theta_f \geq \theta_0$ solve

$$\varphi\left(\theta_f\right) = 0. \tag{A.59}$$

The lower and upper dominance region assumptions ensure that θ_f exists. To show this, note that at $\theta = \theta_0$,

$$\begin{aligned}\varphi\left(\theta_0\right) &= \lambda\bar{l}\left(\theta_0\right) - \lambda d_{\min} - v\left(\theta_0, \bar{l}\left(\theta_0\right)\right)\\ &= \lambda\bar{l}\left(\theta_0\right) - \lambda d_{\min} > 0.\end{aligned} \tag{A.60}$$

Also, for $\theta > \bar{\theta}$, the upper dominance region assumption implies that

$$\begin{aligned}\lambda\bar{l}\left(\theta\right) &< v\left(\theta, 1\right) \leq \lambda\tilde{d}_1 + v\left(\theta, 1\right)\\ &\leq \lambda d^* + v\left(\theta, d^* + A\left(d^*, \hat{d}\right)\right),\end{aligned} \tag{A.61}$$

where $\tilde{d}_1 \geq d_{\min}$ solves $\tilde{d}_1 + A\left(\tilde{d}_1, \hat{d}\right) = 1$. The last inequality in (A.61) comes from individual optimality and feasibility of choosing $d = \tilde{d}_1$ (revealed preference). Thus, $\varphi\left(\theta\right) < 0$ for $\theta > \underline{\theta}$.

Next, Assumption B1 ensures that θ_f is unique. To show this, first note that by the theorem of the maximum $\varphi\left(\theta\right)$ is continuous in θ. Next, notice that (A.56) also implies that d^* is continuous in θ. Differentiating $\varphi\left(\theta\right)$ and applying the envelope theorem, we get

$$\varphi'\left(\theta\right) = \lambda\bar{l}'\left(\theta\right) - v_\theta\left(\theta, d^* + A\left(d^*, \hat{d}\right)\right). \tag{A.62}$$

---

[3]It is straightforward to show that $d^* \leq d_{\min}$ also satisfies the second-order condition

$$v_{ll}\left(\theta, d^* + A\right)\left(1 + A_d\right) + v_l\left(\theta, d^* + A\right)A_{dd} < 0. \tag{A.55}$$

Using $\overline{\ell}' = -\frac{v_\theta}{v_l}$, we get

$$\varphi'(\theta) = -\lambda \frac{v_\theta\left(\theta_0, \overline{\ell}(\theta_0)\right)}{v_l\left(\theta_0, \overline{\ell}(\theta_0)\right)} - v_\theta\left(\theta, d^* + A\left(d^*, \hat{d}\right)\right)$$

$$= v_l\left(\theta, d^* + A(d^*, \hat{d})\right) \frac{v_\theta\left(\theta_0, \overline{\ell}(\theta_0)\right)}{v_l\left(\theta_0, \overline{\ell}(\theta_0)\right)} - v_\theta\left(\theta, d^* + A\left(d^*, \hat{d}\right)\right) \tag{A.63}$$

$$= v_l\left(\theta, d^* + A(d^*, \hat{d})\right) \left(\frac{v_\theta\left(\theta_0, \overline{\ell}(\theta_0)\right)}{v_l\left(\theta_0, \overline{\ell}(\theta_0)\right)} - \frac{v_\theta\left(\theta, d^* + A\left(d^*, \hat{d}\right)\right)}{v_l\left(\theta, d^* + A(d^*, \hat{d})\right)} \right) < 0,$$

where the second line follows from the first order condition $\lambda = -v_l\left(\theta, d^* + A(d^*, \hat{d})\right)$, and the last inequality comes from Assumption B1.

Therefore, any bank with $\theta \leq \theta_f$ optimally sets $d = \overline{\ell}(\theta)$ and $g = 0$, while a bank with $\theta > \theta_f$ sets $d = d^*$ that solves (A.56) and $g = A\left(d^*, \hat{d}\right)$.

Finally, d is discontinuous at $\theta = \theta_f$. with $d\left(\theta_f^-\right) > d\left(\theta_f^+\right)$. $\qquad\square$

Proof of Proposition 2.5.

Consider the condition for the marginal lender (A.68). First, let us multiply both the numerator and denominator on the left-hand side by $\sqrt{\alpha}$. Next, notice that both $\overline{\ell}(\theta)$ and $d^*(\theta)$ are differentiable, by the Implicit function theorem. Also, $\overline{\ell}(\theta)$ is strictly monotone on $[\underline{\theta}, \theta_f]$ and also $d^*(\theta)$ is strictly monotone for $\theta > \theta_f$ for sufficiently large α. To see the latter, note that by the Implicit function theorem, from (2.21) we have that

$$d^{*\prime}(\theta) = \frac{v_{l\theta}(\theta, d^* + A)}{-v_{ll}(\theta, d^* + A)(1 + A_d) - v_l \frac{A_{dd}}{1 + A_d}}$$

$$= -\frac{v_{l\theta}}{\frac{v_l^2}{\lambda} \alpha^{3/2}\left(d^* - \hat{d}\right) \phi\left(\sqrt{\alpha}\left(d^* - \hat{d}\right)\right) - \lambda \frac{v_{ll}}{v_l}},$$

where the second line uses condition (2.21) and the observation that $A_{dd} = \alpha\left(d^* - \hat{d}\right) A_d = -\alpha^{3/2}\left(d^* - \hat{d}\right) \phi\left(\sqrt{\alpha}\left(d^* - \hat{d}\right)\right)$, and note that $\lim_{\alpha \to \infty} \alpha A_d = \lim_{\alpha \to \infty} \alpha^{3/2}\phi\left(\sqrt{\alpha}\left(d^* - \hat{d}\right)\right) = 0$ for any $d^* > \hat{d}$. Therefore, we can use a change of variable to re-write the left-hand side of (A.68) as

$$\frac{\sqrt{\alpha}\phi\left(\hat{d}\right)(\underline{\theta} + K) + \int_0^{\overline{\ell}(\theta_f)} \frac{1}{\overline{\ell}'\left(\overline{\ell}^{-1}(x)\right)} \sqrt{\alpha}\phi\left(\sqrt{\alpha}\left(x - \hat{d}\right)\right) dx}{\int_{d^*(\theta_f)}^{d^*(K)} \frac{1}{d^{*\prime}(d^{*-1}(x))} \sqrt{\alpha}\phi\left(\sqrt{\alpha}\left(x - \hat{d}\right)\right) dx}.$$

Using integration by parts, we further get[4]

$$\frac{\sqrt{\alpha}\phi\left(\sqrt{\alpha}\hat{d}\right)(\underline{\theta}+K)+\frac{\Phi(\sqrt{\alpha}(\bar{\ell}(\theta_f)-\hat{d}))}{\bar{\ell}'(\theta_f)}-\frac{\Phi(\sqrt{\alpha}(-\hat{d}))}{\bar{\ell}'(\underline{\theta})}-\int_0^{\bar{\ell}(\theta_f)}\Phi\left(\sqrt{\alpha}\left(x-\hat{d}\right)\right)\frac{\partial}{\partial x}\left(\frac{1}{\bar{\ell}'\left(\bar{\ell}^{-1}(x)\right)}\right)dx}{\frac{\Phi(\sqrt{\alpha}(d^*(K)-\hat{d}))}{d^{*'}(K)}-\frac{\Phi(\sqrt{\alpha}(d^*(\theta_f)-\hat{d}))}{d^{*'}(\theta_f)}-\int_{d^*(\theta_f)}^{d^*(K)}\Phi\left(\sqrt{\alpha}\left(x-\hat{d}\right)\right)\frac{\partial}{\partial x}\left(\frac{1}{d^{*'}(d^{*-1}(x))}\right)dx}$$

$$=\frac{\sqrt{\alpha}\phi\left(\sqrt{\alpha}\hat{d}\right)(\underline{\theta}+K)+\frac{1-A(\bar{\ell}(\theta_f),\hat{d})}{\bar{\ell}'(\theta_f)}-\frac{1-A(0,\hat{d})}{\bar{\ell}'(\underline{\theta})}-\int_0^{\bar{\ell}(\theta_f)}\left(1-A\left(x,\hat{d}\right)\right)\frac{\partial}{\partial x}\left(\frac{1}{\bar{\ell}'\left(\bar{\ell}^{-1}(x)\right)}\right)dx}{\frac{1-A(d^*(K),\hat{d})}{d^{*'}(K)}-\frac{1-A(d^*(\theta_f),\hat{d})}{d^{*'}(\theta_f)}-\int_{d^*(\theta_f)}^{d^*(K)}\left(1-A\left(x,\hat{d}\right)\right)\frac{\partial}{\partial x}\left(\frac{1}{d^{*'}(d^{*-1}(x))}\right)dx}$$

$$=\frac{\sqrt{\alpha}\phi\left(\sqrt{\alpha}\hat{d}\right)(\underline{\theta}+K)+\frac{1-A(\bar{\ell}(\theta_f),\hat{d})}{\bar{\ell}'(\theta_f)}-\frac{1-A(0,\hat{d})}{\bar{\ell}'(\underline{\theta})}-\int_0^{\bar{\ell}(\theta_f)}\left(1-A\left(x,\hat{d}\right)\right)\frac{\partial}{\partial x}\left(\frac{1}{\bar{\ell}'\left(\bar{\ell}^{-1}(x)\right)}\right)dx}{\frac{1-A(d^*(K),\hat{d})}{d^{*'}(K)}-\frac{1-A(d^*(\theta^f),\hat{d})}{d^{*'}(\theta^f)}-\left(\frac{1}{d^{*'}(K)}-\frac{1}{d^{*'}(\theta_f)}\right)+\int_{d^*(\theta_f)}^{d^*(K)}A\left(x,\hat{d}\right)\frac{\partial}{\partial x}\left(\frac{1}{d^{*'}(d^{*-1}(x))}\right)dx}$$

$$=\frac{\sqrt{\alpha}\phi\left(\sqrt{\alpha}\hat{d}\right)(\underline{\theta}+K)+\frac{1-A(\bar{\ell}(\theta_f),\hat{d})}{\bar{\ell}'(\theta_f)}-\frac{1-A(0,\hat{d})}{\bar{\ell}'(\underline{\theta})}-\int_0^{\bar{\ell}(\theta_f)}\left(1-A\left(x,\hat{d}\right)\right)\frac{\partial}{\partial x}\left(\frac{1}{\bar{\ell}'\left(\bar{\ell}^{-1}(x)\right)}\right)dx}{\frac{A(d^*(K),\hat{d})}{d^{*'}(K)}+\frac{A(d^*(\theta_f),\hat{d})}{d^{*'}(\theta_f)}+\int_{d^*(\theta_f)}^{d^*(K)}A\left(x,\hat{d}\right)\frac{\partial}{\partial x}\left(\frac{1}{d^{*'}(d^{*-1}(x))}\right)dx},$$

where we use $\Phi\left(\sqrt{\alpha}\left(x-\hat{d}\right)\right)=1-\Phi\left(\sqrt{\alpha}\left(\hat{d}-x\right)\right)=1-A\left(x,\hat{d}\right)$ to substitute for the fraction of lenders attacking for a given dividend level x. Notice that from the bank's problem, $\bar{\ell}(\theta_f)\geq d^*\left(\theta^f\right)>d_{\min}>\hat{d}$, for sufficiently large α. Also, the integrals in the numerator and denominator exist for any α, and in the limit, as $\alpha\to\infty$, and lenders are perfectly coordinated, $A\left(x,\hat{d}\right)=$

$$\begin{cases}0 & ,\ x>\hat{d}\\ [0,1] & ,\ x=\hat{d}\\ 1 & ,\ x<\hat{d}\end{cases}.\text{ Thus,}$$

$$\lim_{\alpha\to\infty}\frac{\int_{-K}^{\theta_f}\phi\left(\sqrt{\alpha}\left(\bar{\ell}(\theta)-\hat{d}\right)\right)d\theta}{\int_{\theta_f}^{K}\phi\left(\sqrt{\alpha}\left(d^*(\theta)-\hat{d}\right)\right)d\theta}=\frac{\lim_{\alpha\to\infty}\frac{1}{\bar{\ell}'\left(\bar{\ell}^{-1}(\hat{d})\right)}}{\lim_{\alpha\to\infty}\frac{A(d^*(\theta_f),\hat{d})}{d^{*'}(\theta^f)}}=\frac{1-p}{p}$$

or

$$\lim_{\alpha\to\infty}\frac{A\left(d^*(\theta_f),\hat{d}\right)}{d^{*'}(\theta_f)}=\frac{p}{1-p}\lim_{\alpha\to\infty}\frac{1}{\bar{\ell}'\left(\bar{\ell}^{-1}\left(\hat{d}\right)\right)}.$$

Since $\lim_{\alpha\to\infty}A\left(d^*(\theta_f),\hat{d}\right)=0$, it follows that $d^{*'}(\theta_f)\to 0$, as well.

Next, consider the bank's problem. For $\theta>\theta_f$, we can combine conditions (2.21) and (2.11)

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[4]We implicitly assume that v is differentiable of sufficient order for the expression below.

and write condition (2.21) as

$$\frac{v_l\left(\theta, d_{nr}\left(\theta\right)\right)}{v_l\left(\theta, d^*\left(\theta\right) + A\left(d^*\left(\theta\right), \hat{d}\right)\right)} = 1 + A_d\left(d^*\left(\theta\right), \hat{d}\right). \tag{A.64}$$

In the limit, as $\alpha \to \infty$ and lenders become perfectly coordinated, so $A_d\left(d^*, \hat{d}\right) \to 0$ for $d^* > \hat{d}$. Therefore, from (A.64) we get that

$$\frac{v_l\left(\theta, d_{nr}\left(\theta\right)\right)}{v_l\left(\theta, d^*\left(\theta\right)\right)} \to 1,$$

and so $d^*\left(\theta\right) \to d_{nr}\left(\theta\right)$. In addition, in the limit, the marginal bank that is indifferent between failing and surviving experiences no run in equilibrium, since $\lim_{\alpha\to\infty} A\left(d^*\left(\theta_f\right), \hat{d}\right) = 0$. Therefore, condition (2.20) implies that

$$\lambda \bar{\ell}\left(\theta_f\right) = \lambda d^*\left(\theta_f\right) + v\left(\theta_f, d^*\left(\theta_f\right)\right).$$

However, by the definition of θ^* in (2.10), this in turn implies that $\theta_f \to \theta^*$ and $d^*\left(\theta_f\right) \to \bar{\ell}\left(\theta^*\right)$. Finally, note that

$$d^{*\prime}\left(\theta_f\right) = -\frac{v_{l\theta}}{\frac{v_l^2}{\lambda}\alpha^{3/2}\left(d^*\left(\theta_f\right) - \hat{d}\right)\phi\left(\sqrt{\alpha}\left(d^*\left(\theta_f\right) - \hat{d}\right)\right) - \lambda\frac{v_{ll}}{v_l}} \to 0$$

implies that $\alpha^{3/2}\left(d^*\left(\theta_f\right) - \hat{d}\right)\phi\left(\sqrt{\alpha}\left(d^*\left(\theta_f\right) - \hat{d}\right)\right) \to \infty$, which can only be the case if $\hat{d} \to d^*\left(\theta_f\right)$. □

Proofs of results in Section 2.5

Proof of Proposition 2.6.

Suppose that $d = 0$, $\forall\theta$ and instead lenders obtain dispersed private signals about θ as in Section 2.3.1. Let us denote the failure threshold in that case by $\tilde{\theta}_f$. In that case, Proposition A.1 implies that $\tilde{\theta}_f$ solves

$$\bar{l}\left(\tilde{\theta}_f\right) = p.$$

In contrast with arbitrarily precise dividend signals, Proposition 2.5 implies that the failure threshold $\theta_f \to \theta^*$. Thus whenever $\bar{\ell}\left(\theta^*\right) < p$, it follows that $\theta^* < \tilde{\theta}_f$. □

Proof of Proposition 2.7.

A proportional tax on dividends $\tau > 0$ decreases the effective value of λ to $\tilde{\lambda} = (1 - \tau)\lambda$. With arbitrarily precise dividend signals, Proposition 2.5 implies that the failure threshold $\theta_f \to \theta^*$, where θ^* solves $\lambda = -v_l\left(\theta^*, \bar{\ell}\left(\theta^*\right)\right)$. With a proportional tax, τ, $\theta^*\left(\tau\right)$ solves

$$\tilde{\lambda} = (1 - \tau)\lambda = -v_l\left(\theta^*\left(\tau\right), \bar{\ell}\left(\theta^*\left(\tau\right)\right)\right).$$

By the implicit function theorem, we have

$$\frac{\partial \theta^*}{\partial \tau} = -\frac{\partial \theta^*}{\partial \lambda} = \frac{1}{v_{l\theta} + v_{ll}\frac{\partial \bar{l}}{\partial \theta}} = \frac{1}{\frac{1}{v_l}\left(v_{l\theta}v_l - v_{ll}v_\theta\right)}.$$

Note that by Assumption B1,

$$\frac{\partial}{\partial l}\left(\frac{v_\theta}{v_l}\right) = \frac{v_{l\theta}v_l - v_{ll}v_\theta}{v_l^2} > 0,$$

it follows that $\frac{\partial \theta^*}{\partial \tau} < 0$. □

A.3   A continuum of dividend levels – details

This part of the appendix contains the details of the analysis of the equilibrium when banks can issue any feasible dividend level given their type. First, we derive conditions under which a lender i's posterior belief about the bank failing, $\Pr(\theta < \theta_f|d_i)$, is decreasing in d_i. Let us define two probability densities,

$$\psi_{N,i}(x) = \frac{\phi\left(\sqrt{\alpha}\left(\bar{\ell}(x) - d_i\right)\right)}{\int_{-K}^{\theta_f} \phi\left(\sqrt{\alpha}\left(\bar{\ell}(z) - d_i\right)\right)dz}, \text{ for } x \in [-K, \theta_f], \tag{A.65}$$

and

$$\psi_{D,i}(x) = \frac{\phi\left(\sqrt{\alpha}\left(d^*(x) - d_i\right)\right)}{\int_{\theta_f}^{K} \phi\left(\sqrt{\alpha}\left(d^*(z) - d_i\right)\right)dz}, \text{ for } x \in [\theta_f, K]. \tag{A.66}$$

with corresponding cdf given by $\Psi_{N,i}(x)$ and $\Psi_{D,i}(x)$, respectively. Analogously, we define the expectation operators with respect to the two densities by $E_{N,i}[.]$ (resp., $E_{D,i}[.]$). The following lemma characterizes the lenders' inference based on their signals about d.

Lemma A.6. *The posterior belief of a lender observing signal d_i, $\Pr_i\{\theta < \theta_f|d_i\}$, is strictly decreasing in d_i iff*

$$E_{N,i}\left[\bar{\ell}(\theta)\right] < E_{D,i}\left[d^*(\theta)\right]. \tag{A.67}$$

Proof. It will be useful to work with the posterior odds that the bank fails, i.e.

$$h(d_i, \theta_f) \equiv \frac{\Pr\{\theta < \theta_f|d_i\}}{\Pr\{\theta > \theta_f|d_i\}} = \frac{\int_{-K}^{K} f(d_i|\theta) f\left(\theta|\theta < \theta^f\right) d\theta \Pr\{\theta < \theta_f\}}{\int_{-K}^{K} f(d_i|\theta) f\left(\theta|\theta > \theta^f\right) d\theta \Pr\{\theta > \theta_f\}}$$

$$= \frac{\int_{-K}^{\theta_f} \phi\left(\sqrt{\alpha}\left(\bar{\ell}(\theta) - d_i\right)\right) d\theta}{\int_{\theta_f}^{K} \phi\left(\sqrt{\alpha}\left(d^*(\theta) - d_i\right)\right) d\theta},$$

where the last line uses the symmetry of the normal pdf around the mean and an improper prior over θ. Let

$$N(d_i, \theta_f) \equiv \int_{-K}^{\theta_f} \sqrt{\alpha}\phi\left(\sqrt{\alpha}\left(\bar{\ell}(\theta) - d_i\right)\right) d\theta,$$

and

$$D\left(d_i, \theta_f\right) \equiv \int_{\theta_f}^{K} \sqrt{\alpha}\phi\left(\sqrt{\alpha}\left(d^*\left(\theta\right) - d_i\right)\right) d\theta.$$

Then

$$h\left(d_i, \theta_f\right) = \frac{N\left(d_i, \theta_f\right)}{D\left(d_i, \theta_f\right)},$$

and so

$$\log\left(h\left(d_i, \theta_f\right)\right) = \log\left(N\left(d_i, \theta_f\right)\right) - \log\left(D\left(d_i, \theta_f\right)\right).$$

Therefore, $h\left(d_i, \theta_f\right)$ is decreasing in d_i, iff $\log\left(h\left(d_i, \theta_f\right)\right)$ is decreasing in d_i, which will be the case iff

$$\frac{N_{d_i}}{N} < \frac{D_{d_i}}{D}.$$

Note that

$$
\begin{aligned}
\frac{N_{d_i}}{N} &= -\frac{\int_{-K}^{\theta_f} \phi'\left(\sqrt{\alpha}\left(\bar{\ell}\left(\theta\right) - d_i\right)\right) d\theta}{\int_{-K}^{\theta_f} \phi\left(\sqrt{\alpha}\left(\bar{\ell}\left(\theta\right) - d_i\right)\right) d\theta} \\
&= \int_{-K}^{\theta_f} \alpha\left(\bar{\ell}\left(\theta\right) - d_i\right)\frac{\phi\left(\sqrt{\alpha}\left(\bar{\ell}\left(\theta\right) - d_i\right)\right)}{\int_{-K}^{\theta_f} \phi\left(\sqrt{\alpha}\left(\bar{\ell}\left(\theta\right) - d_i\right)\right) dz}d\theta \\
&= \alpha\left\{E_{N,i}\left[\bar{\ell}\left(\theta\right)\right] - d_i\right\}.
\end{aligned}
$$

Similarly,

$$\frac{D_x}{D} = \alpha\left\{E_{D,i}\left[d^*\left(\theta\right)\right] - d_i\right\}$$

Therefore, the comparison simplifies to

$$\alpha\left\{E_{N,i}\left[\bar{\ell}\left(\theta\right)\right] - d_i\right\} < \alpha\left\{E_{D,i}\left[d^*\left(\theta\right)\right] - d_i\right\}$$

or

$$E_{N,i}\left[\bar{\ell}\left(\theta\right)\right] < E_{D,i}\left[d^*\left(\theta\right)\right].$$

$\square$

Intuitively, Lemma A.6 states that if a lender with signal d_i expects a lower dividend payment from a bank that fails compared to a bank that survives (where expectations are taken with respect to the densities ψ_N and ψ_D, respectively), then a lender with a marginally higher signal is more optimistic about the bank surviving. Put differently, whenever condition (A.67) is satisfied for some d_i, observing a marginally higher d_i constitutes good news about the bank surviving.

Notice, however, that by the lower dominance assumption, $\bar{\ell}\left(\theta\right) = 0$ for $\theta \leq \underline{\theta}$. Therefore, we can re-write $E_{N,i}\left[\bar{\ell}\left(\theta\right)\right]$ as

$$
\begin{aligned}
E_{N,i}\left[\bar{\ell}\left(\theta\right)\right] &= \left(1 - \Psi_{N,i}\left(\underline{\theta}\right)\right)E_{N,i}\left[\bar{\ell}\left(\theta\right) | \theta \in \left[\underline{\theta}, \theta_f\right]\right], \\
&\leq \left(1 - \Psi_{N,i}\left(\underline{\theta}\right)\right)\bar{l}\left(\theta_f\right) \leq 1 - \Psi_{N,i}\left(\underline{\theta}\right)
\end{aligned}
$$

where the first inequality follows from the strict monotonicity of $\bar{\ell}(\theta)$ and the second inequality follows from the observation that $\theta_f \leq \bar{\theta}$ and the upper dominance region assumption. On the other hand, by the properties of $d^*(\theta)$, $E_{D,i}[d^*(\theta)] > d_{\min}$. However, as we show in the proof of Lemma A.7 below, for any d_i, $\Psi_{N,i}(\underline{\theta})$ can be made arbitrarily close to 1 for sufficiently large K. Intuitively, whenever K is large, the conditional probability that a failing bank has a fundamental below the lower dominance threshold and issues a dividend of 0 given that it fails is large. Therefore, observing a higher value of d_i increases the likelihood that the lender is facing a failing bank with fundamental above the lower dominance threshold only slightly. In contrast, it increases substantially the likelihood that it is a surviving bank. Overall, this implies that a higher value of d_i is good news about the bank being above the failure threshold.

We use this observation to characterize the lenders' actions below.

Lemma A.7. *Suppose that banks with $\theta < \theta_f$ fail, where $\theta_f \leq \bar{\theta}$ is given in (2.20) and that banks follow the dividend policy given in (2.22). There exists a $\overline{K}$ such that for $K > \overline{K}$, there is a lender with signal $d_i = \hat{d}$, where $\hat{d}$ is uniquely determined by*

$$\frac{\int_{-K}^{\theta_f} \phi\left(\sqrt{\alpha}\left(\bar{\ell}(\theta) - \hat{d}\right)\right) d\theta}{\int_{\theta_f}^{K} \phi\left(\sqrt{\alpha}\left(d^*(\theta) - \hat{d}\right)\right) d\theta} = \frac{1-p}{p} \tag{A.68}$$

who is indifferent between running and rolling over, where $\phi(.)$ denotes the standard normal p.d.f. Furthermore, a lender observing $d_i < \hat{d}$ is strictly better off from running, while a lender observing $d_i > \hat{d}$ is strictly worse off from running.

Proof. A lender with signal $\hat{d}$ is indifferent between running and rolling over whenever

$$\Pr\left\{\theta < \theta_f | \hat{d}\right\} = 1 - p,$$

or equivalently,

$$\frac{\Pr\left\{\theta < \theta_f | \hat{d}\right\}}{\Pr\left\{\theta > \theta_f | \hat{d}\right\}} = \frac{1-p}{p}.$$

Next, by the discussion immediately after Lemma A.6, we have that

$$E_{N,i}\left[\bar{\ell}(\theta)\right] \leq 1 - \Psi_{N,i}(\underline{\theta}).$$

However, observe that

$$
\begin{aligned}
\Psi_{N,i}\left(\underline{\theta}\right) &= \frac{\int_{-K}^{\underline{\theta}} \phi\left(\sqrt{\alpha}\left(\bar{\ell}\left(z\right)-d_i\right)\right)dz}{\int_{-K}^{\theta_f} \phi\left(\sqrt{\alpha}\left(\bar{\ell}\left(z\right)-d_i\right)\right)dz} \\
&= \frac{\phi\left(\sqrt{\alpha}\left(d_i\right)\right)\left(\underline{\theta}+K\right)}{\phi\left(\sqrt{\alpha}\left(d_i\right)\right)\left(\underline{\theta}+K\right)+\int_{\underline{\theta}}^{\theta_f} \phi\left(\sqrt{\alpha}\left(\bar{\ell}\left(z\right)-d_i\right)\right)dz} \\
&= \frac{1}{1+\frac{1}{\underline{\theta}+K}\int_{\underline{\theta}}^{\theta_f} \frac{\phi\left(\sqrt{\alpha}\left(\bar{\ell}\left(z\right)-d_i\right)\right)}{\phi\left(\sqrt{\alpha}d_i\right)}dz} \\
&\geq \frac{1}{1+\frac{\theta_f-\underline{\theta}}{\underline{\theta}+K}\max_{z\in\left[\underline{\theta},\theta_f\right]}\frac{\phi\left(\sqrt{\alpha}\left(\bar{\ell}\left(z\right)-d_i\right)\right)}{\phi\left(\sqrt{\alpha}d_i\right)}}
\end{aligned}
$$

Therefore, for sufficiently larger values of K one can ensure that $E_{N,i}\left[\bar{\ell}\left(\theta\right)\right] < d_{\min} < E_{D,i}\left[d^*\left(\theta\right)\right]$ for any d_i. Therefore, by Lemma A.6, $\Pr\left\{\theta < \theta_f | d_i\right\}$ is monotone decreasing in d_i, and so is $\frac{\Pr\left\{\theta<\theta_f|d_i\right\}}{\Pr\left\{\theta>\theta_f|d_i\right\}}$. Also, clearly, $\frac{\Pr\left\{\theta<\theta_f|d_i\right\}}{\Pr\left\{\theta>\theta_f|d_i\right\}}$ can be made arbitrarily large (arbitrarily close to 0) for sufficiently small (large) d_i. Therefore, by the intermediate value theorem, there exists a unique marginal lender with signal $\hat{d}$ that satisfies (A.68). By the strict monotonicity of $\frac{\Pr\left\{\theta<\theta_f|d_i\right\}}{\Pr\left\{\theta>\theta_f|d_i\right\}}$, for any lender with $d_i < \hat{d}$, $\frac{\Pr\left\{\theta<\theta_f|d_i\right\}}{\Pr\left\{\theta>\theta_f|d_i\right\}} < \frac{1-p}{p}$, so that lender is strictly better off attacking. Similarly, any lender with $d_i > \hat{d}$ is strictly better off not attacking. $\qquad\square$

Next, we derive a condition under which in any monotone strategy equilibrium of this economy, the cutoff $\hat{d} \in (0,1)$. To this end, we first characterize the optimal dividend policy of a bank that faces a run of $A = 1$ irrespective of its fundamentals θ.

Lemma A.8. *Consider a bank that does face a run by all lenders, i.e. $A = 1$, suppose that $\lambda \geq -v_l\left(\underline{\theta}, 0\right)$, and let $d_r\left(\theta\right)$ denote the bank's optimal dividend policy. Then banks with $\theta < \bar{\theta}$ choose $d_r\left(\theta\right) = \bar{l}\left(\theta\right)$, while banks with $\theta \geq \bar{\theta}$ choose $d_r\left(\theta\right) = d^*$, where d^* solves the first-order condition*

$$
\left(\lambda + v_l\left(\theta, d^*+1\right)\right)d^* = 0. \tag{A.69}
$$

Proof. First, notice that by the multiplicity region assumption, if $A = 1$, then any bank with $\theta < \bar{\theta}$ knows that it will fail for sure, so it is optimal for it to set $d_r\left(\theta\right) = \bar{\ell}\left(\theta\right)$. Next, for $\theta \geq \bar{\theta}$, the bank is better off surviving, given the upper dominance region assumption. In that case, it solves

$$
\tilde{W}\left(\theta\right) = \max_{d\in\left[0,\bar{\ell}\left(\theta\right)\right]}\left\{\lambda d + v\left(\theta, d+1\right)\right\}.
$$

Taking the f.o.c. with respect to d, the optimal d^* solves

$$
\lambda \leq -v_l\left(\theta, d^*\right).
$$

Therefore, d^* satisfies condition (A.69). $\qquad\square$

Next, let us define $\hat{d}_{\max}$ as the unique solution to

$$\frac{\int_{-K}^{\overline{\theta}} \phi\left(\sqrt{\alpha}\left(\overline{\ell}\left(\theta\right) - \hat{d}_{\max}\right)\right) d\theta}{\int_{\underline{\theta}}^{K} \phi\left(\sqrt{\alpha}\left(d_r\left(\theta\right) - \hat{d}_{\max}\right)\right) d\theta} = \frac{1-p}{p}. \tag{A.70}$$

By Lemma A.6 and the discussion after it, it follows that for any α, there is a sufficiently large K, such that the left-hand side of (A.70) is decreasing in $\hat{d}_{\max}$ and so (A.61) can have at most one solution. Furthermore, the left-hand side of that expression can be made arbitrarily large (arbitrarily close to 0) for sufficiently small (large) values of $\hat{d}_{\max}$ and so there exists a solution. We can now state condition B3 which ensures that in any monotone equilibrium, $\hat{d} < 1$.

Assumption B3. $\hat{d}_{\max} < 1$.

Notice that $\hat{d}_{\max}$ is the signal of a marginal lender who is indifferent between running and rolling over if all other lenders run irrespective of their signal, and hence banks suffer a run of $A = 1$ irrespective of θ. Therefore, this is the lender cutoff in the most pessimistic possible case, when other lenders run irrespective of their signals and only banks in the upper dominance region survive. As we show in the proof of Proposition A.2 below, this condition then ensures that in any monotone strategy equilibrium, $\hat{d} < \hat{d}_{\max} < 1$.

Similarly, let $\hat{d}_{\min}$ be the unique solution to

$$\frac{\int_{-K}^{\theta^*} \phi\left(\sqrt{\alpha}\left(\overline{\ell}\left(\theta\right) - \hat{d}_{\min}\right)\right) d\theta}{\int_{\theta^*}^{K} \phi\left(\sqrt{\alpha}\left(d_{nr}\left(\theta\right) - \hat{d}_{\min}\right)\right) d\theta} = \frac{1-p}{p}, \tag{A.71}$$

where θ^* and $d_{nr}\left(\theta\right)$ were defined in Lemma 2.1 that examines optimal bank behavior in the case of no run. As with the case of $\hat{d}_{\max}$ it is straightforward to show that for sufficiently large K, $\hat{d}_{\min}$ is unique. Condition B4 then is analogous to condition B3:

Assumption B4. $\hat{d}_{\min} > 0$.

Therefore, $\hat{d}_{\min}$ is the signal of a marginal lender who is indifferent between running and rolling over if all other lenders roll over irrespective of their signal and hence the bank experiences no run for any θ. Therefore, this is the lender cutoff in the most optimistic possible case, when other lenders do not run irrespective of their signal and only banks with $\theta < \theta^*$ fail. As we show in the proof of Proposition A.2 below, this condition then ensures that in any monotone strategy equilibrium, $\hat{d} > \hat{d}_{\min} > 0$.

We can combine the results from Lemmas 2.1 and A.7 to characterize equilibria in monotone strategies for this economy. An equilibrium in monotone strategies consists of a lender cutoff $\hat{d}$, bank cutoff θ_f and a bank dividend policy $d\left(\theta\right)$.

Proposition A.2. *Consider equilibria of this economy, in which lenders follow a monotone strategy with cutoff at $\hat{d}$. In those equilibria banks fail according to a cutoff θ_f, and $\hat{d}$ and θ_f jointly satisfy conditions (A.68) and (2.20), where the banks follow a dividend policy $d(\theta)$ given by equation (2.22). Furthermore, if θ_f and $\hat{d}$ are unique, and assumptions B3 and B4 hold, then the unique monotone strategy equilibrium is also the unique equilibrium of this economy.*

The first part of the proposition follows directly from the partial characterization results in Lemmas 2.1 and A.7. To show the second part, let $\hat{d}^*$ and θ_f^* denote the unique solutions to (A.68) and (2.20). We will use the notation $\theta_f(x)$, $x \in (0,1)$, for the bank failure threshold given that lenders use a monotone strategy with cutoff at x and similarly, $\hat{d}(x) = \hat{d}(\theta_f(x))$, $x \in (0,1)$, for the signal of a marginal agent given that lenders are using a monotone strategy with cutoff at x, and so, the bank failure cutoff is $\theta_f(x)$. First of all, applying the implicit function theorem and the envelope theorem on equation (2.20), we get

$$\frac{\partial \theta_f}{\partial \hat{d}} = \frac{v_l A_d}{v_\theta \left(\frac{v_l + \lambda}{v_l}\right)}.$$

Furthermore, substituting for

$$\frac{v_l + \lambda}{v_l} = -A_d$$

from equation (2.21), we get

$$\frac{\partial \theta_f}{\partial \hat{d}} = -\frac{v_l}{v_\theta} > 0.$$

Similarly, from equation (A.68), and given that $\Pr\{\theta < \theta_f | d_i\}$ is strictly decreasing in d_i by the discussion preceding Lemma A.7, we have that $\frac{\partial \hat{d}}{\partial \theta_f} > 0$, and so,

$$\frac{\partial \hat{d}}{\partial x} = \frac{\partial \hat{d}}{\partial \theta_f} \frac{\partial \theta_f}{\partial x} > 0. \tag{A.72}$$

Next, let us define recursively two sequences, $\{\underline{\delta}_n\}_{n=0}^{\infty}$ and $\{\overline{\delta}_n\}_{n=0}^{\infty}$, in the following way. Let $\overline{\delta}_0 = \infty$, $\overline{\delta}_1 = \hat{d}_{\max}$, where $\hat{d}_{\max}$ was defined in (A.70) above, and $\overline{\delta}_n = \hat{d}(\overline{\delta}_{n-1})$, for $n \geq 2$. Given Assumption B3, one can define $\overline{\delta}_2 = \hat{d}(\hat{d}_{\max})$ in this way. Similarly, let $\underline{\delta}_0 = -\infty$, $\underline{\delta}_1 = \hat{d}_{\min}$, where $\hat{d}_{\min}$ was defined in (A.71), and $\underline{\delta}_n = \hat{d}(\underline{\delta}_{n-1})$, for $n \geq 2$. Given Assumption B4, one can define $\underline{\delta}_2 = \hat{d}(\hat{d}_{\min})$ in this way. By condition (A.72), it follows that $\{\underline{\delta}_n\}_{n=0}^{\infty}$ is a strictly increasing sequence. Furthermore, it is bounded above by $\hat{d}^*$. Therefore, $\{\underline{\delta}_n\}_{n=0}^{\infty}$ converges. Let us denote the limiting value of that sequence by $\underline{\delta}_\infty$. Since $\hat{d}^* = \hat{d}(\hat{d}^*)$ and $\hat{d}(x)$ is continuous in x, it follows that $\underline{\delta}_\infty = \hat{d}^*$. Similarly, $\{\overline{\delta}_n\}_{n=0}^{\infty}$ is a strictly decreasing sequence bounded below by $\hat{d}^*$ and it converges to $\overline{\delta}_\infty = \hat{d}^*$. In the case when $\hat{d}$ and θ^f are not uniquely determined, let $\hat{d}_L$ and $\hat{d}_H$ denote the smallest and largest values of $\hat{d}$. In that case, $\underline{\delta}_\infty$ converges to $\hat{d}_L$ and $\overline{\delta}_\infty$ converges to $\hat{d}_H$. In the latter case, $\overline{\delta}_n \leq \hat{d}_{\max} < 1$, $n \geq 1$, and so $\hat{d}_H < 1$. Thus Assumption B3 implies that $\hat{d} < 1$ in any monotone strategy equilibrium of this economy. Similarly, Assumption B4 implies that $\hat{d} > 0$. $\quad\square$

Details for the numerical example in Section 2.4

In Section 2.4 we show the results from a numerical example to illustrate the equilibrium dividend payments for banks when the precision of lender signals is large but finite. For this numerical example we assume that $v(\theta, l) = \theta \ln(\theta - l)$ for $1 \le \theta < 2$, $v(\theta, l) = 0$, for $\theta < 1$, and $v(\theta, l) = \theta \ln(\theta - l) + Z$, $Z > 0$, for $\theta \ge 2$.[5] Therefore, the lower-dominance region is $\theta \le \underline{\theta} = 1$, while the upper dominance region (provided Z is sufficiently large) is $\theta \ge \bar{\theta} = 2$. Note also that $d_{nr}(\theta) = \begin{cases} \theta - 1 & , \ \theta \le \lambda \\ \left(1 - \frac{1}{\lambda}\right)\theta & , \ \theta > \lambda \end{cases}$, so the bank's dividend policy is piece-wise linear with a kink at $\theta = \lambda$ and the bank liquidates all assets at $\theta^* = \lambda$. We solve for the equilibrium in two cases, a low precision case in which $\sigma = 0.05$ and a high-precision case with $\sigma = 0.001$. The other parameters for this example are $p = 0.5$, and $\lambda = 1.1$

A.4 Data

The following table contains an overview over the data we use. All bank data are from the Federal Reserves Y-9C reports and are at the bank-holding company level. All firm data used when comparing across industries are from Compustat. For Compustat firms, we compute dividends paid from CRSP.

---

[5]This payoff assumption violates the condition that v is continuously differentiable everywhere. However, it is a convenient way to ensure the existence of an upper dominance region. Also, all of the analytical results hold in this case as well.

Variable	Source	Definition	Variable name in source
Repo	Federal FR Y-9C Reports	Securities sold under agreements to repurchase	BHCKB995
Dividends (bank)	Federal FR Y-9C Reports	Cash dividends declared on common stock	BHCK4460
Liquid assets	Federal FR Y-9C Reports	Cash and cash-like instruments + treasuries	Sum of several variables
Cash	Federal FR Y-9C Reports	Noninterest-bearing balances and currency and coin	BHCK0081
Cash-like instrument	Federal FR Y-9C Reports	Interest-bearing balances in U.S offices	BHCK0395
Treasuries	Federal FR Y-9C Reports	US Treasuiers, both market and amortized value.	BHCK0211,BHCK0213,BHCK1286,BHCK1287
Total Assets	Federal FR Y-9C Reports	Total Assets	BHCP2170
Total Assets	Compustat	Assets - total	at
Current liabilities	Compustat	Current liabilities - total	lct
Liabilities	Compustat	Liabilities - Total	lt
Dividends	CRSP	Dividend per share	divamt
Total number of shares	CRSP	Total number of outstanding shares	shrout

Table A.1: Variables and definitions - bank and firm data.

Appendix B

Appendix to Chapter 3

B.1 Omitted proofs

Proof of Proposition 1

The L1 agents utility differential from choosing $a_i = 1$ over $a_i = 0$ is

$$\pi_i^{L1} \quad = \quad \Pr_i \left\{ \theta < \theta_{L0}^f \right\} E_i \left[D\left(\theta\right) | \theta < \theta_{L0}^f \right] - x.$$

We denote the strategic threshold of L1 types by θ_{L1}^*. That threshold satisfies

$$\hat{\pi}^{L1} = \int_{-\infty}^{\theta_{L0}^f} D\left(\theta\right) \frac{1}{\sigma} \phi \left(\frac{\theta - \theta_{L1}^*}{\sigma} \right) d\theta - x = 0.$$

In the case where there are only L1 types, (true) failure threshold θ_{L1}^f satisfies

$$g\left(\theta_{L1}^f \right) = \Phi \left(\frac{\theta_{L1}^* - \theta_{L1}^f}{\sigma} \right).$$

Notice that $\frac{\hat{\pi}^{L1}}{\theta_{L1}^*} < 0$ since a more optimistic agent has a lower payoff from attacking. Also, we can use a change of variables $z = \frac{\theta - \theta_{L1}^*}{\sigma}$ to write $\hat{\pi}^{L1}$ as

$$\hat{\pi}^{L1} = \int_{-\infty}^{\frac{\theta_{L0}^f - \theta_{L1}^*}{\sigma}} D\left(\theta_{L1}^* + \sigma z \right) \phi\left(z \right) dz - x.$$

Therefore,

$$
\frac{\partial \hat{\pi}^{L1}}{\partial \sigma}\bigg|_{\theta_{L1}^* - fixed} = D\left(\theta_{L0}^f\right)\phi\left(\frac{\theta_{L0}^f - \theta_{L1}^*}{\sigma}\right)\frac{1}{\sigma}\left[-\frac{\theta_{L0}^f - \theta_{L1}^*}{\sigma} + \frac{\partial \theta_{L0}^f}{\partial \sigma}\right]
$$
$$
+ \int_{-\infty}^{\frac{\theta_{L0}^f - \theta_{L1}^*}{\sigma}} D'\left(\theta_{L1}^* + \sigma z\right) z \phi\left(z\right) dz,
$$

or undoing the change of variable in the second term,

$$
\frac{\partial \hat{\pi}^{L1}}{\partial \sigma}\bigg|_{\theta_{L1}^* - fixed} = D\left(\theta_{L0}^f\right)\phi\left(\frac{\theta_{L0}^f - \theta_{L1}^*}{\sigma}\right)\frac{1}{\sigma}\left[-\frac{\theta_{L0}^f - \theta_{L1}^*}{\sigma} + \frac{\partial \theta_{L0}^f}{\partial \sigma}\right]
$$
$$
+ \frac{1}{\sigma}\int_{-\infty}^{\theta_{L0}^f} D'\left(\theta\right)\left(\theta - \theta_{L1}^*\right)\frac{1}{\sigma}\phi\left(\frac{\theta - \theta_{L1}^*}{\sigma}\right) d\theta,
$$
$$
= \frac{1}{\sigma}\left\{D\left(\theta_{L0}^f\right)\phi\left(\frac{\theta_{L0}^f - \theta_{L1}^*}{\sigma}\right)\left[-\frac{\theta_{L0}^f - \theta_{L1}^*}{\sigma} + \frac{\partial \theta_{L0}^f}{\partial \sigma}\right] - E_{\theta_{L1}^*}\left[S\left(\theta\right)\left(\theta - \theta_{L1}^*\right)\right]\right\}
$$

where $S\left(\theta\right) = \begin{cases} |D'\left(\theta\right)| & ,\theta < \theta_{L0}^f \\ 0 & ,\theta > \theta_{L0}^f \end{cases}$. Therefore,

$$
\frac{\partial \theta_{L1}^*}{\partial \sigma} \propto -E_{\theta_{L1}^*}\left[S\left(\theta\right)\left(\theta - \theta_{L1}^*\right)\right] + D\left(\theta_{L0}^f\right)\phi\left(\frac{\theta_{L0}^f - \theta_{L1}^*}{\sigma}\right)\left[\frac{\theta_{L1}^* - \theta_{L0}^f}{\sigma} + \frac{\partial \theta_{L0}^f}{\partial \sigma}\right]
$$

which depends on a comparison of θ_{L0}^f, θ_{L0}^*, and θ_{L1}^*. $\qquad\square$

B.2 Additional model predictions and analysis

In this appendix, we present additional model predictions and analysis.

Additional model predictions

In addition to the model prediction presented in the main body of the text, the class of models we consider have two additional predictions.

Model prediction a . Players with signal realization above Y^* attack and players with signal realization below Y^* do not attack.

Given that agents follow a monotone strategy Y^*, all agents will receive a signal above their strategic threshold whenever $Y > Y^* + \epsilon$. Correspondingly, all agents will receive a signal below Y^* whenever $Y < Y^* - \epsilon$.

Model prediction b. Probability of regime change is 1 if $Y > Y^* + \epsilon$. Probability of regime change is 0 if $Y < Y^* - \epsilon$. Probability of regime change is increasing in Y for $Y \in [Y^* - \epsilon, Y^* + \epsilon]$

As a direct consequence of model prediction a, for regimes of a type $Y > Y^* + \epsilon$, all agents must have received a signal above their strategic threshold and hence attack. When all agent's attack, the regime fails with probability 1 provided that $Y > \underline{Y}$. Similarly, for regimes of a type $Y < Y^* - \epsilon$ no agents attack and the probability of regime change is 0.

The two additional model predictions yields the three additional hypothesis:

Hypothesis a: $Y^*_{T1} = 41.38$ and $Y^*_{T2} = 37.79$.

Hypothesis b: $\Pr(B|x_i) > 0.5$ if $x_i > \hat{Y}^*_j$ (model prediction 2).

Hypothesis c: $\Pr(\mathcal{R} = 1|Y) = \begin{cases} 1 & : Y > Y^*_j + \epsilon_j \\ 0 & : Y < Y^*_j - \epsilon_j \end{cases}$

and increasing for $Y^* - \epsilon_j \leq Y \leq Y^* + \epsilon_j$ (model prediction 4) where Y is short-hand for the realized fundamental in each situation-period.

Additional results

The strategic threshold in T2 is significantly higher relative to the theory-implied threshold. The strategic threshold in T1 is indistinguishable from the theory-implied threshold.

Table B.1 reports the results from performing a simple t-test on whether the estimated strategic thresholds is significantly different than the thresholds predicted by theory. We can reject the null hypothesis that the estimated threshold is equal to the theory-implied in T2 (the high noise treatment) with a p-value of 4 %, but not in T1. Furthermore, the strategic threshold in the high noise treatment is **higher** than what implied by the theory, suggesting that subjects are less willing to attack when the noise is large compared to what the theory predict.
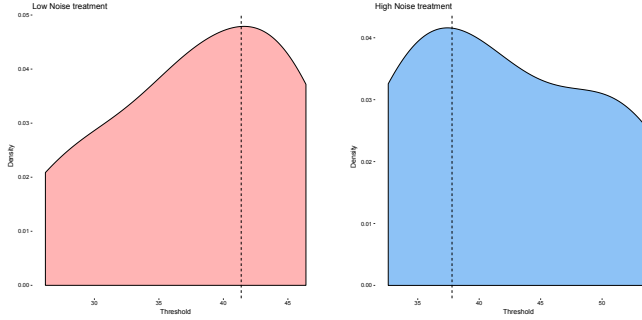
Figure B.1: Kernel densities for low-noise treatment (left panel) and high-noise treatment (right panel). Vertical dashed lines correspond to the respective theory-implied strategic thresholds.

	T1 (low noise)	T2 (high noise)
Average estimated strategic threshold	37.9	42.3
Predicted threshold	41.38	37.79
p-value	0.34	0.04

Table B.1: Results from t-test, testing differences between estimated strategic thresholds and theory-predicted strategic thresholds.

In Figure B.1, we plot the estimated kernel densities for the two treatments and the theory-implied thresholds.

Agents are less likely to attack in T2 compared to theory.

Hypothesis a states that the probability of observing subjects choosing B ("attack") should exceed 0.5 whenever subjects receive signals higher than the theory-implied strategic thresholds. In Figure B.2 we plot the predicted probability of attacking conditional in the private signal from estimating equation (3.7) for the two treatments.

The figure reflects Result 1. In T1, subjects are close to playing the theory implied strategy. In T2, subjects are more cautious compared to theory. That is, $\Pr(B_i|x_i) < 0.5$ for some $x_i > Y^*_{T2}$.

In each treatment, likelihood that the regime fails is 1 if $Y > Y^* + \epsilon$ and 0 if $Y < Y^* - \epsilon$.

Letting Y^* denote the strategic thresholds implied by the theory, Hypothesis c says that the probability of regime change $\Pr(\mathcal{R} = 1|Y)$ is 1 if the true value of the fundamentals $Y > Y^* + \epsilon$ and 0 if $Y < Y^* - \epsilon$. We evaluate how the observed behavior is consistent with this hypothesis by fitting a cumulative logistic regression

$$\Pr(\mathcal{R} = 1|Y) = \frac{1}{1 + \exp(\alpha - \beta Y)} \tag{B.1}$$
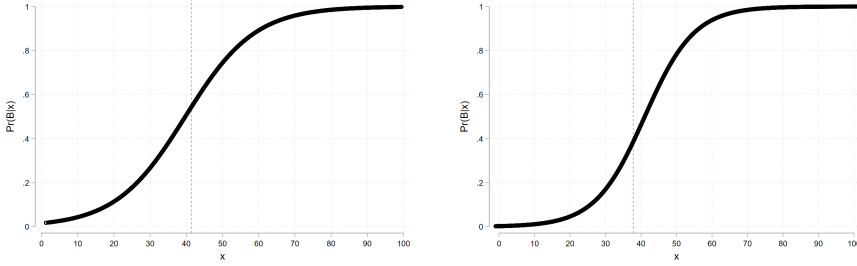
Figure B.2: Predicted probability of attacking from estimating equation (3.7) for the low-noise treatment T1 (left panel) and the high-noise treatment T2 (right panel). Vertical red lines correspond .

Figure B.3 shows the estimated $\Pr(\mathcal{R} = 1|Y)$ for realized values of the fundamentals Y . The vertical lines correspond to $Y^* - \epsilon$ and $Y^* + \epsilon$. As is clear from the figure, as Y is increasing the probability of regime change is increasing. Furthermore, for $Y > Y^* + \epsilon$ the regime always fails ($\mathcal{R} = 1$) and for $Y < Y^* - \epsilon$ the regime always survive in T2. In T1, the regime always survive if $Y < Y^* - \epsilon$.

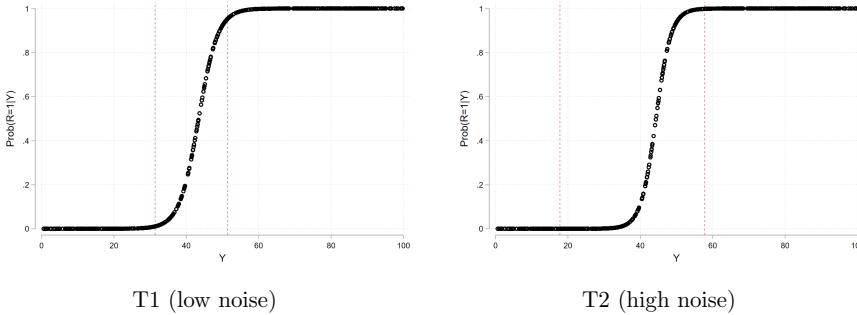T1 (low noise)   T2 (high noise)

Figure B.3: Predicted probability of attacking from estimating equation (B.1) for the low-noise treatment T1 (left panel) and the high-noise treatment T2 (right panel). Vertical red lines correspond to the treatment-specific $Y_j^* \pm \epsilon_j$.

Overall, the figure supports Hypothesis c.

Appendix C

Appendix to Chapter 4
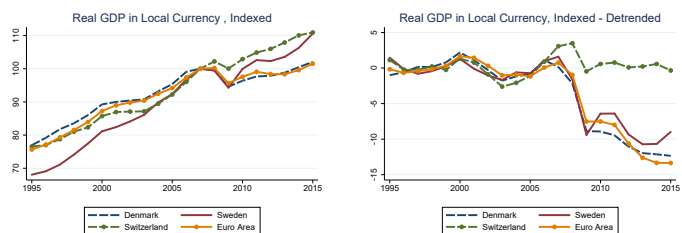
C.1   Additional figures

Figure C.1: Gross domestic product in constant prices. Local currency. Indexed so that GDP^{2008}=100. The right panel shows the detrended series using a linear time trend based on the 1995-2007 period.
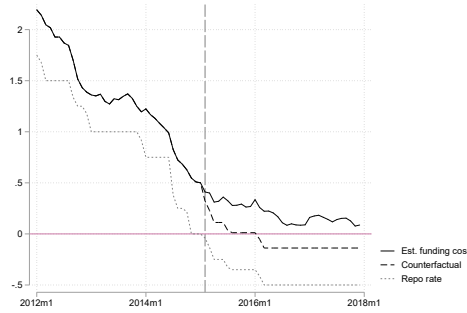
Figure C.2: Estimated average funding costs. The estimated average funding cost is computed by taking the weighted average of the assumed interest rate of the different funding sources of the bank. Certificates are assumed to have the same interest rate as STIBOR 3M, while unsecured debt are assumed to have the same interest rate as STIBOR 3M plus a 2 percent constant risk-premium. The "counterfactual" series correspond to the case when the spread between the repo rate and the estimated funding cost remain fixed at pre-negative levels. Weights from Figure 4.11 used.
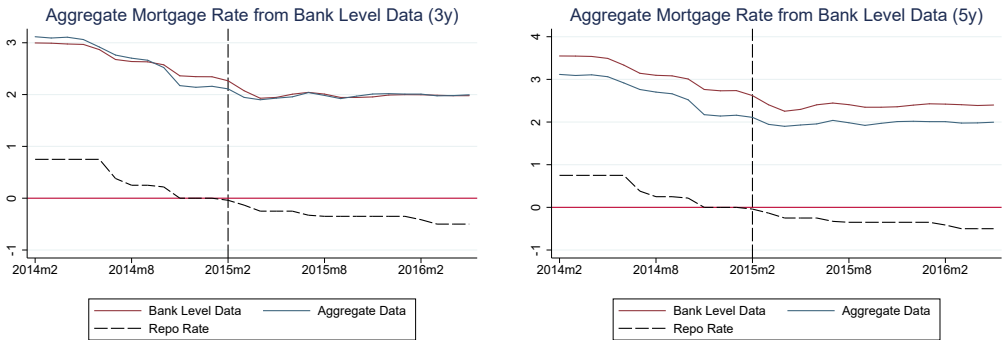

Figure C.3: Comparing bank level mortgage rates to aggregate data. We aggregate the bank level mortgage rates using market shares from the Swedish Banker's Association (2017), supplemented with data on lending volumes from Statistics Sweden. The blue line (Aggregate Data) depicts the official average mortgage interest rate for loans with a fixed interest rate period of 3-5 years from Statistics Sweden.

C.2   Details of the model

Households

We consider a closed economy, populated by a unit-measure continuum of households. Households are of two types, either patient (indexed by superscript s) or impatient (indexed by superscript b). Patient households have a higher discount factor than impatient agents, i.e. $\beta^s > \beta^b$. The total mass of patient households is $1 - \chi$, while the total mass of impatient households is χ. In equilibrium,

impatient households will borrow from patient households via the banking system, which we specify below. We therefore refer to the impatient households as "borrowers" and the patient households as "savers".

Households consume, supply labor, borrow/save and hold real money balances. At any time t, the optimal choice of consumption, labor, borrowing/saving and money holdings for a household $j \in \{s, b\}$ maximizes the present value of the sum of utilities

$$\mathcal{U}_t^j = \mathbb{E}_t \sum_{T=t}^{\infty} \left(\beta^j\right)^{T-t} \left[U\left(C_T^j\right) + \Omega\left(\frac{M_T^j}{P_T}\right) - V\left(N_T^j\right)\right] \zeta_t \tag{C.1}$$

where ζ_t is a random variable following some stochastic process and acts as a preference shock.[1] C_t^j and N_t^j denote consumption and labor for type j respectively, and the utility function satisfies standard assumptions clarified below.

Households consume a bundle of consumption goods. Specifically, there is a continuum of goods indexed by i, and each household j has preferences over the consumption index

$$C_t^j = \left(\int_0^1 C_t\left(i\right)^{\frac{\theta-1}{\theta}} di\right)^{\frac{\theta}{\theta-1}} \tag{C.2}$$

where $\theta > 1$ measures the elasticity of substitution between goods.

Agents maximize lifetime utility (equation (C.1)) subject to the following flow budget constraint:

$$M_t^j + B_{t-1}^j \left(1 + i_{t-1}^j\right) = W_t^j N_t^j + B_t^j + M_{t-1}^j - P_t C_t^j - S\left(M_{t-1}^j\right) + \Psi_t^j + \psi_t^j - T_t^j \tag{C.3}$$

B_t^j denotes one period risk-free debt of type j ($B_t^s < 0$ and $B_t^b > 0$). For the saver, B_t^s consists of bank deposits and government bonds, both remunerated at the same interest rate i_t^s by arbitrage. Borrower households borrow from the bank sector only, at the bank's lending rate i_t^b. $S\left(M_{t-1}^j\right)$ denotes the storage cost of holding money. Ψ_t^j is type j's share of firm profits, and ψ_t^j is type j's share of bank profits. Let Z_t^{firm} denote firm profits, and Z_t denote bank profits. We assume that firm profits are distributed to both household types based on their population shares, i.e. $\Psi_t^b = \chi Z_t^{firm}$ and $\Psi_t^s = (1-\chi)Z_t^{firm}$. Bank profits on the other hand are only distributed to savers, which own the deposits by which banks finance themselves.[2] Hence, we have that $\psi_t^b = 0$ and $\psi_t^s = Z_t$.

The optimal consumption path for an individual of type j has to satisfy the standard Euler-equation

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[1]We introduce the preference shock as a parsimonious way of engineering a recession.

[2]Distributing bank profits to both household types would make negative interest rates even more contractionary. The reduction in bank profits would reduce the transfer income of borrower households, causing them to reduce consumption. We believe this effect to be of second order significance, and so we abstract from it here.

$$U'\left(C_t^j\right)\zeta_t = \beta^j\left(1 + i_t^j\right)\mathbb{E}_t\left(\Pi_{t+1}^{-1}U'\left(C_{t+1}^j\right)\zeta_{t+1}\right) \tag{C.4}$$

Optimal labor supply has to satisfy the intratemporal trade-off between consumption and labor[3]

$$\frac{V'\left(N_t^j\right)}{U'\left(C_t^j\right)} = \frac{W_t^j}{P_t} \tag{C.5}$$

Finally, optimal holdings of money have to satisfy[4]

$$\frac{\Omega'\left(\dfrac{M_t^j}{P_t}\right)}{U'\left(C_t^j\right)} = \frac{i_t^j + S'\left(M_t^j\right)}{1 + i_t^j} \tag{C.6}$$

The lower bound on the deposit rate $\underline{i}^s$ is typically defined as the lowest value of i_t^s satisfying equation (C.6). The lower bound therefore depends crucially on the marginal storage cost. With the existence of a satiation point in real money balances, zero (or constant) storage costs imply $S'\left(M_t^s\right) = 0$ and $\underline{i}^s = 0$. That is, the deposit rate is bounded at exactly zero. With a non-zero marginal storage cost however, this is no longer the case. If storage cost are convex, for instance, the marginal storage cost is increasing in M_t^s. In this case, there is no lower bound. Based on the data from section (4.2), a reasonable assumption is that the deposit rate is bounded at some value close to zero. This is consistent with a proportional storage cost $S\left(M_t^s\right) = \gamma M_t^s$, with a small $\gamma > 0$. We therefore assume proportional storage costs for the rest of the paper, in which the lower bound on deposit rates is given by $\underline{i}^s = -\gamma$.[5]

We assume that households have exponential preferences over consumption, i.e. $U(C_t^j) = 1 - exp\{-qC_t^j\}$ for some $q > 0$. The assumption of exponential utility is made for simplicity, as it facilitates aggregation across agents. Under these assumptions, the labor-consumption trade-off can easily be aggregated into an economy-wide labor market condition[6]

$$\frac{V'\left(N_t\right)}{U'\left(C_t\right)} = \frac{W_t}{P_t} \tag{C.7}$$

Letting G_t denote government spending[7], aggregate demand is given by

$$Y_t = \chi C_t^b + (1 - \chi) C_t^s + G_t \tag{C.8}$$

---

[3]We assume that the function V is increasing in N and convex with well defined first and second derivatives.

[4]We assume a satiation point for money. That is, at some level $\bar{m}^j$ households become satiated in real money balances, and so $\Omega'(\bar{m}^j) = 0$.

[5]This nests the case of no storage costs, in which case $\gamma = 0$.

[6]To see this, just take the weighted average of equation (C.5) using the population shares χ and $1 - \chi$ as the respective weights.

[7]Government policies are explained below.

Firms

Each good i is produced by a firm i. Production is linear in labor, i.e.

$$Y_t(i) = N_t(i) \tag{C.9}$$

where $N_t(i)$ is a Cobb-Douglas composite of labor from borrowers and savers respectively, i.e. $N_t(i) = \left(N_t^b(i)\right)^\chi \left(N_t^s(i)\right)^{1-\chi}$, as in Benigno, Eggertsson, and Romei (2014). This ensures that each type of labor receives a total compensation equal to a fixed share of total labor expenses. That is,

$$W_t^b N_t^b = \chi W_t N_t \tag{C.10}$$
$$W_t^s N_t^s = (1-\chi) W_t N_t \tag{C.11}$$

where $W_t = \left(W_t^b\right)^\chi \left(W_t^s\right)^{1-\chi}$ and $N_t = \int_0^1 N_t(i)\,di$.

Given preferences, firms face a downward-sloping demand function

$$Y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\theta} Y_t \tag{C.12}$$

We introduce nominal rigidities by assuming Calvo-pricing. That is, in each period, a fraction α of firms are not able to reset their price. Thus, the likelihood that a price set in period t applies in period $T > t$ is α^{T-t}. Prices are assumed to be indexed to the inflation target Π.

A firm that is allowed to reset their price in period t sets the price to maximize the present value of discounted profits in the event that the price remains fixed. That is, each firm i choose $P_t(i)$ to maximize

$$\mathbb{E}_t \sum_{T=t}^{\infty} (\alpha\beta)^{T-t} \lambda_T \left[\Pi^{T-t}\frac{P_t(i)}{P_T}Y_T(i) - \frac{W_T}{P_T}Y_T(i)\right] \tag{C.13}$$

where $\lambda_T \equiv q\left(\chi\exp\left\{-qC_T^b\right\} + (1-\chi)\exp\left\{-qC_T^s\right\}\right)$, which is the weighted marginal utility of consumption and $\beta \equiv \chi\beta^b + (1-\chi)\beta^s$.[8]

Denoting the markup as $\mu \equiv \dfrac{\theta}{\theta-1}$, firms set the price as a markup over the average of expected marginal costs during the periods the price is expected to remain in place. That is, the first-order

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[8]Recall that the firm is owned by both types of households according to their respective population shares.

condition for the optimal price $P(i)_t^*$ for firm i is

$$\frac{P(i)_t^*}{P_t} = \mu \frac{\mathbb{E}_t\left\{\sum_{T=t}^{\infty}(\alpha\beta)^{T-t}\lambda_T\left(\frac{P_T}{P_t}\frac{1}{\Pi^{T-t}}\right)^{\theta}\frac{W_T}{P_T}Y_T\right\}}{\mathbb{E}_t\left\{\sum_{T=t}^{\infty}(\alpha\beta)^{T-t}\lambda_T\left(\frac{P_T}{P_t}\frac{1}{\Pi^{T-t}}\right)^{\theta-1}\frac{W_T}{P_T}Y_T\right\}} \tag{C.14}$$

This implies a law of motion for the aggregate price level

$$P_t^{1-\theta} = (1-\alpha)P_t^{*1-\theta} + \alpha P_{t-1}^{1-\theta}\Pi^{1-\theta} \tag{C.15}$$

where P_t^* is the optimal price from equation (C.14), taking into account that in equilibrium $P_t^*(i)$ is identical for all i. We denote this price P_t^*.

Since prices are sticky, there exists price dispersion which we denote by

$$\Delta_t \equiv \int_0^1 \left(\frac{P_t(i)}{P_t}\right)^{-\theta} di \tag{C.16}$$

with the law of motion

$$\Delta_t = \alpha\left(\frac{\Pi_t}{\Pi}\right)^{\theta}\Delta_{t-1} + (1-\alpha)\left(\frac{1-\alpha\left(\frac{\Pi_t}{\Pi}\right)^{\theta-1}}{1-\alpha}\right)^{\frac{\theta}{\theta-1}} \tag{C.17}$$

We assume that the disutility of labor takes the form $V(N_t^j) = \frac{(N^j)^{1+\eta}}{1+\eta}$. We can then combine equations (C.14) - (C.17), together with the aggregate labor-consumption trade-off (equation (C.7)) to get an aggregate Phillips curve of the following form:

$$\left(\frac{1-\alpha\left(\frac{\Pi_t}{\Pi}\right)^{\theta-1}}{1-\alpha}\right)^{\frac{1}{\theta-1}} = \frac{F_t}{K_t} \tag{C.18}$$

where

$$F_t = \lambda_t Y_t + \alpha\beta\mathbb{E}_t\left\{F_{t+1}\left(\frac{\Pi_{t+1}}{\Pi}\right)^{\theta-1}\right\} \tag{C.19}$$

and

$$K_t = \mu\frac{\lambda_t\Delta_t^{\eta}Y_t^{1+\eta}}{z\exp\{-zY_t\}} + \alpha\beta\mathbb{E}_t\left\{K_{t+1}\left(\frac{\Pi_{t+1}}{\Pi}\right)^{\theta}\right\} \tag{C.20}$$

and

$$\lambda_T \equiv z \left(\chi \exp \left\{ -q C_T^b \right\} + (1 - \chi) \exp \left\{ -q C_T^s \right\} \right) \tag{C.21}$$

Since every firm faces demand $Y(i) = \left(\dfrac{P_t(i)}{P_t} \right)^{-\theta} Y_t$ and $Y_t(i) = N_t(i)$, we can integrate over all firms to get that

$$N_t = \Delta_t Y_t \tag{C.22}$$

Banks

Our banking sector is made up of identical, perfectly competitive banks. Bank assets consist of one-period real loans l_t. In addition to loans, banks hold real reserves $R_t \geq 0$ and real money balances $m_t = \dfrac{M_t}{P_t} \geq 0$, both issued by the central bank.[9] Bank liabilities consist of real deposits d_t. Reserves are remunerated at the interest rate i_t^r, which is set by the central bank. Loans earn a return i_t^b. The cost of funds, i.e. the deposit rate, is denoted i_t^s. Banks take all of these interest-rates as given.

Financial intermediation takes up real resources. Therefore, in equilibrium there is a spread between the deposit rate i_t^s and the lending rate i_t^b. We assume that bank's intermediation costs are given by a function $\Gamma \left(\dfrac{l_t}{\bar{l}_t}, R_t, m_t, z_t \right)$, in which $z_t = \dfrac{Z_t}{P_t}$ is real bank profit. In order to allow for the intermediation cost to be time-varying for a given set of bank characteristics, we include a stochastic cost-shifter $\bar{l}_t$. This cost-shifter may capture time-variation in borrowers default probabilities, changes in borrower households borrowing capacity, bank regulation etc. (Benigno, Eggertsson, and Romei 2014).

We assume that the intermediation costs are increasing and convex in the amount of real loans provided. That is, $\Gamma_l > 0$ and $\Gamma_{ll} \geq 0$. Central bank currency plays a key role in reducing intermediation costs[10]. The marginal cost reductions from holding reserves and money are captured by $\Gamma_R \leq 0$ and $\Gamma_m \leq 0$ respectively. We assume that the bank becomes satiated in reserves for some level $\bar{R}$. That is, $\Gamma_R = 0$ for $R \geq \bar{R}$. Similarly, banks become satiated in money at some level $\bar{m}$, so that $\Gamma_m = 0$ for $m \geq \bar{m}$. Banks can thus reduce their intermediation costs by holding reserves and/or cash, but the opportunity for cost reduction can be exhausted. Finally, we assume that higher profits (weakly) reduce the marginal cost of lending. That is, we assume $\Gamma_{lz} \leq 0$. We discuss this assumption below.

Following Curdia and Woodford (2011) and Benigno, Eggertsson, and Romei (2014) we assume that any real profits from the bank's asset holdings are distributed to their owners in period t and that the bank holds exactly enough assets at the end of the period to pay off the depositors in

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[9]Because we treat the bank problem as static - as outlined below - we can express the maximization problem in real terms.

[10]For example, we can think about this as capturing in a reduced form way the liquidity risk that banks face. When banks provide loans, they take on costly liquidity risk because the deposits created when the loans are made have a stochastic point of withdrawal. More reserves helps reduce this expected cost.

period $t + 1$.[11] Furthermore, we assume that storage costs of money are proportional and given by $S(M) = \gamma M$. Under these assumptions, real bank profits can be implicitly expressed as:

$$z_t = \frac{i_t^b - i_t^s}{1 + i_t^s} l_t - \frac{i_t^s - i_t^r}{1 + i_t^s} R_t - \frac{i_t^s + \gamma}{1 + i_t^s} m_t - \Gamma\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right) \tag{C.23}$$

Any interior l_t, R_t and m_t have to satisfy the respective first-order conditions from the bank's optimization problem[12]

$$l_t \quad : \quad \frac{i_t^b - i_t^s}{1 + i_t^s} = \frac{1}{\bar{l}_t} \Gamma_l\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right) \tag{C.24}$$

$$R_t \quad : \quad -\Gamma_R\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right) = \frac{i_t^s - i_t^r}{1 + i_t^s} \tag{C.25}$$

$$m_t \quad : \quad -\Gamma_m\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right) = \frac{i_t^s + \gamma}{1 + i_t^s} \tag{C.26}$$

The first-order condition for real loans says that the banks trade off the marginal profits from lending with the marginal increase in intermediation costs. The next two first-order conditions describe banks demand for reserves and cash. We assume that reserves and money are not perfect substitutes, and so minimizing the intermediation cost implies holding both reserves and money. This is not important for our main result.[13]

The first-order condition for loans pins down the equilibrium credit spread ω_t defined as

$$\omega_t \equiv \frac{1 + i_t^b}{1 + i_t^s} - 1 = \frac{i_t^b - i_t^s}{1 + i_t^s} \tag{C.27}$$

Specifically, it says that

$$\omega_t = \frac{1}{\chi \bar{b}_t} \Gamma_l\left(\frac{b_t^b}{\bar{b}_t}, R_t, m_t, z_t\right) \tag{C.28}$$

where we have used the market clearing condition in equation (C.29) to express the spread as a function of the borrowers real debt holdings b_t^b.[14]

$$l_t = \chi b_t^b \tag{C.29}$$

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[11]The latter is equivalent to assuming that $\left(1 + i_t^b\right) l_t + \left(1 + i_t^r\right) R_t + m_t - S\left(m_t\right) = \left(1 + i_t^s\right) d_t$.

[12]Assuming that $\Gamma\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right)$ is such that there exists a unique z solving equation (C.23).

[13]The assumption that banks always wants to hold some reserves is however important for the effect of negative interest rates on bank profitability. If we instead assume that the sum of money holdings and reserves enters the banks cost function as one argument, the bank would hold only money once $i^r < -\gamma$. Hence, reducing the interest rate on reserves further would not affect bank profits. However, such a collapse in central bank reserves is not consistent with data, suggesting that banks want to hold some (excess) reserves.

[14]Following equation (C.29) we also assume that $\bar{l}_t = \chi \bar{b}_t$.

That is, the difference between the borrowing rate and the deposit rate is an increasing function of the aggregate relative debt level, and a decreasing function of bank's net worth.

Why do bank profits affect intermediation costs?   We have assumed that the marginal cost of extending loans (weakly) decreases with bank profits. That is, $\Gamma_{lz} \leq 0$. This assumption captures, in a reduced form manner, the established link between bank's net worth and their operational costs. We do not make an attempt to microfound this assumption here, which is explicitly done in among others Holmstrom and Tirole (1997) and Gertler and Kiyotaki (2010).[15]

In Gertler and Kiyotaki (2010) bank managers may divert funds, which means that banks must satisfy an incentive compatibility constraint in order to obtain external financing. This constraint limits the amount of outside funding the bank can obtain based on the banks net worth. Because credit supply is determined by the total amount of internal and external funding, this means that bank lending depends on bank profits. In an early contribution, Holmstrom and Tirole (1997) achieve a similar link between credit supply and bank net worth by giving banks the opportunity to engage (or not engage) in costly monitoring of its non-financial borrowers. For recent empirical evidence on the relevance of bank net worth in explaining credit supply, see for example Jiménez, Ongena, Peydró, and Saurina (2012).

Importantly, our main result is that negative interest rates are *not expansionary*. This does not depend on profits affecting intermediation costs. However, the link between profits and the intermediation cost is the driving force behind negative interest rates being *contractionary*. If we turn off this mechanism, negative interest rates still reduce bank profits, but this does not feed back into aggregate demand.[16]

Policy

The consolidated government budget constraint is given by

$$B_t^g + M_t^{tot} + P_t R_t = (1 + i_{t-1}^g)B_{t-1}^g + M_{t-1}^{tot} + (1 + i_{t-1}^r)P_t R_{t-1} + G_t - T_t \qquad \text{(C.30)}$$

where B_t^g is one period government debt, $M_t^{tot} = M_t + M_t^s + M_t^b$ is total money supply - which is the sum of money held by banks and each household type, i_t^g is the one period risk-free rate on government debt, G_t is government spending, and $T_t = \chi T_t^b + (1 - \chi) T_t^s$ is the weighted sum of taxes on the two household types.

The conventional way of defining monetary and fiscal policy, abstracting from reserves and the banking sector (see e.g. Woodford 2003b), is to say that fiscal policy is the determination of end of period government liabilities, i.e. $B_t^g + M_t^{tot}$, via the fiscal policy choice of G_t and T_t. Monetary

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[15]Another way to interpret the implied link between bank profits and credit supply is to include a capital requirement. In Gerali, Neri, Sessa, and Signoretti (2010) a reduction in bank profits reduces the bank's capital ratio. In order to recapitalize the bank lowers credit supply.

[16]Alternatively, we could assume that bank profits do not affect intermediation costs, but that bank profits are distributed to all households. A reduction in bank profits would then reduce aggregate demand through the borrowers budget constraint.

policy on the other hand, determines the *split* of end of period government liabilities B_t^g and M_t^{tot}, via open market operations. This in turn determines the risk-free nominal interest rate i_t^g through the money demand equations of the agents in the economy. The traditional assumption then, is that the one period risk-free rate on government debt corresponds to the policy rate which the monetary authority controls via the supply of money through the money demand equation.

We define monetary and fiscal policy in a similar way here. Fiscal policy is the choice of fiscal spending G_t and taxes T_t. This choice determines total government liabilities at the end of period t – the left hand side of equation (C.30). Total government liabilities are now composed of public debt and the money holdings of each agent, as well as reserves held at the central bank. Again, monetary policy is defined by how total government liabilities is split between government bonds B_t^g, and the overall supply of central bank issuance. In addition, we assume that the central bank sets the interest rate on reserves i_t^r. The supply of central bank currency is then given by

$$CBC_t = P_t R_t + M_t + M_t^s + M_t^b \tag{C.31}$$

Given these assumptions, the financial sector itself determines the allocation between reserves and money. That is, the split between the money holdings of different agents and reserves held by banks is an endogenous market outcome determined by the first order conditions of banks and households.

In order to clarify the discussion, it is helpful to review two policy regimes observed in the US at different times. Consider first the institutional arrangement in the US prior to the crisis, when the Federal Reserve paid no interest on reserves, so that $i_t^r = 0$. As seen from equation (C.25), this implies that banks were not satiated in reserves. The policy maker then chose CBC_t so as to ensure that the risk-free rate was equal to its target. In this more general model, the policy rate is simply the risk-free nominal interest rate, which is equal to the deposit rate and, assuming that depositors can also hold government bonds, the interest rate paid on one period government bonds, i.e. $i_t^s = i_t^g$.

Consider now an alternative institutional arrangement, in which paying interest on reserves is a policy tool. Such a regime seems like a good description of the post-crisis monetary policy operations, both in the US and elsewhere. The central bank now sets the interest rate on reserves equal to the risk-free rate, i.e. $i_t^r = i_t^s = i_t^g$, and chooses CBC_t to implement its desired target. From the first order condition for reserves (C.25), we see that $i_t^s = i_t^r$ implies that $\Gamma_R = 0$. Hence, as long as banks are satiated in reserves, the central bank implicitly controls i_t^s via i_t^r. A key point, however, is that $\Gamma_R = 0$ is not always feasible due to the lower bound on the deposit rate. If the deposit rate is bounded at $\underline{i}^s = -\gamma$, and the central bank lowers i_t^r below $-\gamma$, then $i_t^s > i_t^r$. The first order condition then implies $\Gamma_R > 0$. Intuitively, it is not possible to keep banks satiated in reserves when they are being charged for their reserve holdings. More explicitly, we assume that the interest rate on reserves follows a Taylor rule given by equation (C.32). Because of the reserve management policy outlined above, the deposit rate in equilibrium is either equal to the reserve rate or to the lower bound, as specified in equation (C.33). We can now ask a well defined question:

what happens if the interest rate on reserves is lowered below the lower bound on the deposit rate?

$$i_t^r = r_t^n \Pi_t^{\phi_\pi} Y_t^{\phi_Y} \tag{C.32}$$

$$i_t^s = \max \left\{ \underline{i}^s, i_t^r \right\} \tag{C.33}$$

Before closing this section it is worth pointing out that it seems exceedingly likely that there also exists a lower bound on the reserve rate. Reserves are useful for banks because they are used to settle cash-balances between banks at the end of each day. However, banks could in principle settle these balances outside of the central bank, for example by ferrying currency from one bank to another (or more realistically trade with a privately owned clearing house where the commercial banks can store cash balances). Hence, because banks have the option to exchange their reserves for cash, there is a limit to how negative i_t^r can become. We do not model this bound here, as it does not appear to have been breached (yet) in practice. Instead we focus on the bound on deposit rates - which is observable in the data.

Equilibrium

Non-linear Equilibrium Conditions

For given initial conditions Δ_0, b_0^b and a sequence of shocks $\left\{ \zeta_t, \bar{l}_t \right\}_{t=0}^{\infty}$, an equilibrium in our model is a sequence of endogenous prices $\left\{ i_t^s, i_t^b, i_t^r \right\}_{t=0}^{\infty}$ and endogenous variables

$\{ C_t^b, C_t^s, b_t^b, m_t^b, m_t^s, \tau_t^s, cbc_t, Y_t, \Pi_t, F_t, K_t, \Delta_t, \lambda_t, l_t, R_t, m_t, z_t \}_{t=0}^{\infty}$ such that the 20 equations listed below are satisfied.

$$\exp\left\{-qC_t^b\right\}\zeta_t = \beta^b\left(1+i_t^b\right)\mathbb{E}_t\left(\Pi_{t+1}^{-1}\exp\left\{-qC_{t+1}^b\right\}\right)\zeta_{t+1} \tag{C.34}$$

$$\exp\left\{-qC_t^s\right\}\zeta_t = \beta^s\left(1+i_t^s\right)\mathbb{E}_t\left(\Pi_{t+1}^{-1}\exp\left\{-qC_{t+1}^s\right\}\right)\zeta_{t+1} \tag{C.35}$$

$$C_t^b + m_t^b + \frac{1+i_{t-1}^b}{\Pi_t}b_{t-1}^b = \chi Y_t + \frac{1-\gamma}{\Pi_t}m_{t-1}^b + b_t^b \tag{C.36}$$

$$\frac{\Omega'\left(m_t^b\right)}{U'\left(C_t^b\right)} = \frac{i_t^b+\gamma}{1+i_t^b} \tag{C.37}$$

$$\frac{\Omega'\left(m_t^s\right)}{U'\left(C_t^s\right)} = \frac{i_t^s+\gamma}{1+i_t^s} \tag{C.38}$$

$$\Pi_t cbc_t = cbc_{t-1} + i_{t-1}^r R_{t-1} - \Pi_t \tau_t^s \tag{C.39}$$

$$cbc_t = R_t + m_t + m_t^s + m_t^b \tag{C.40}$$

$$Y_t = \chi C_t^b + (1-\chi)C_t^s \tag{C.41}$$

$$\left(\frac{1-\alpha\left(\frac{\Pi_t}{\Pi}\right)^{\theta-1}}{1-\alpha}\right)^{\frac{1}{\theta-1}} = \frac{F_t}{K_t} \tag{C.42}$$

$$F_t = \lambda_t Y_t + \alpha\beta\mathbb{E}_t\left\{F_{t+1}\left(\frac{\Pi_{t+1}}{\Pi}\right)^{\theta-1}\right\} \tag{C.43}$$

$$K_t = \mu\frac{\lambda_t\Delta_t^\eta Y_t^{1+\eta}}{q\exp\left\{-qY_t\right\}} + \alpha\beta\mathbb{E}_t\left\{K_{t+1}\left(\frac{\Pi_{t+1}}{\Pi}\right)^\theta\right\} \tag{C.44}$$

$$\lambda_t = q\left(\chi\exp\left\{-qC_t^b\right\} + (1-\chi)\exp\left\{-qC_t^s\right\}\right) \tag{C.45}$$

$$\Delta_t = \alpha\left(\frac{\Pi_t}{\Pi}\right)^\theta\Delta_{t-1} + (1-\alpha)\left(\frac{1-\alpha\left(\frac{\Pi_t}{\Pi}\right)^{\theta-1}}{1-\alpha}\right)^{\frac{\theta}{\theta-1}} \tag{C.46}$$

$$z_t = \frac{i_t^b-i_t^s}{1+i_t^s}l_t - \frac{i_t^s-i_t^r}{1+i_t^s}R_t - \frac{i_t^s+\gamma}{1+i_t^s}m_t - \Gamma\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right) \tag{C.47}$$

$$\frac{i_t^b-i_t^s}{1+i_t^s} = \frac{1}{\bar{l}_t}\Gamma_l\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right) \tag{C.48}$$

$$-\Gamma_R\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right) = \frac{i_t^s-i_t^r}{1+i_t^s} \tag{C.49}$$

$$-\Gamma_m\left(\frac{l_t}{\bar{l}_t}, R_t, m_t, z_t\right) = \frac{i_t^s+\gamma}{1+i_t^s} \tag{C.50}$$

$$i_t^r = r_t^n\Pi_t^{\phi_\pi}Y_t^{\phi_Y} \tag{C.51}$$

$$i_t^s = \max\left\{-\gamma, i_t^r\right\} \tag{C.52}$$

$$l_t = \chi b_t^b \tag{C.53}$$

Steady state

We denote the steady-state value of a variable X_t as X.

First, observe that in steady-state inflation is at the inflation target Π . As a result, there is no

price dispersion ($\Delta = 1$).

Combining this with the Phillips curve, we have that steady-state output is pinned down by the following equation

$$\mu \frac{Y^\eta}{q \exp\{-qY\}} = 1 \tag{C.54}$$

From the Euler equation of a household of type j we have that

$$1 + i^j = \frac{\Pi}{\beta^j} \tag{C.55}$$

Using the steady-state interest rates, we can jointly solve for all bank-variables. Notice that in steady-state banks are satiated in reserves, and so $R = \overline{R}$ by assumption. Furthermore, if the intermediation cost function is additive between money and the other arguments (which we assume, see below), the steady-state level of money holdings for banks is independent of other bank variables. Therefore, only bank profits and bank lending have to be solved jointly.

Given total debt and interest rates, the borrowers budget constraint and money demand can be solved for steady state consumption and money holdings:

$$C^b = \chi Y + \frac{\Pi - 1 - i^b}{\Pi} b^b - \frac{\Pi - 1 + \gamma}{\Pi} m^b \tag{C.56}$$

$$\Omega'(m^b) = \frac{i^b + \gamma}{1 + i^b} U'\left(C^b\right) \tag{C.57}$$

Then, using the aggregate resource constraint we have that

$$C^s = \frac{1 - \chi^2}{1 - \chi} Y + \frac{\chi}{1 - \chi} \left(\frac{\Pi - 1 - i^b}{\Pi} b^b - \frac{\Pi - 1 + \gamma}{\Pi} m^b \right) \tag{C.58}$$

The savers money demand follows from

$$\Omega'(m^s) = \frac{i^s + \gamma}{1 + i^s} U'(C^s) \tag{C.59}$$

Finally, given the steady-state holdings of reserves and real money balances we can use the total money supply equation and the consolidated government budget constraint to solve for the remaining variables.

Log-linearized equilibrium conditions

We log linearize the non-linear equilibrium conditions around steady state, and define $\hat{X} \equiv \frac{X_t - X}{X}$. For the intermediation cost function we assume the following functional form

$$
\Gamma\left(\frac{l_t}{\bar{\bar{l}}_t}, R_t, m_t, z_t\right) = \begin{cases} \left(\frac{l_t}{\bar{\bar{l}}_t}\right)^{\nu}(z_t)^{-\iota} + \frac{1}{2}\left(R_t - \overline{R}\right)^2 + \frac{1}{2}\left(m_t - \overline{m}\right)^2 & \text{if } R_t < \overline{R} \text{ and } m_t < \overline{m} \\ \left(\frac{l_t}{\bar{\bar{l}}_t}\right)^{\nu}(z_t)^{-\iota} & \text{if } R_t \geq \overline{R} \text{ and } m_t \geq \overline{m} \end{cases}
$$

(C.60)

By combining the two Euler equations and the aggregate demand equation we derive the IS curve in equation (C.61), in which we define $\sigma = \frac{1}{q^Y}$. By combining the five supply side equations we derive the Phillips curve in equation (C.70). We define the real interest rate $\hat{r}^n_t$ in equation (C.62), and the interest rate spread in equation (C.71). We also use the market clearing condition to substitute $\hat{l}_t$ for $\hat{b}^b_t$. Hence, an equilibrium of the log-linearized model is a process for the 17 endogenous variables $\left\{\hat{c}^b_t, \hat{c}^s_t, \hat{b}^b_t, \hat{m}^b_t, \hat{m}^s_t, \hat{y}_t, \hat{r}^n_t, \hat{\pi}_t, \hat{\tau}^s, \hat{cbc}_t, \hat{m}_t, \hat{R}_t, \hat{z}_t, \hat{\omega}_t, \hat{i}^b_t, \hat{i}^s_t, \hat{i}^r_t\right\}_{t=0}^{\infty}$ such that the 17 equations listed below are satisfied. Note that the expressions for $\hat{R}_t$ and $\hat{m}_t$, in equations (C.74) and (C.75) respectively, only hold when the bank is not satiated.

$$\hat{y}_t = \mathbb{E}_t \hat{y}_{t+1} - \sigma \left(\hat{i}_t^s - \mathbb{E}_t \hat{\pi}_{t+1} - \hat{r}_t^n \right) \tag{C.61}$$

$$\hat{r}_t^n = \hat{\zeta}_t - \mathbb{E}_t \hat{\zeta}_{t+1} - \chi \hat{\omega}_t \tag{C.62}$$

$$\hat{c}_t^b = \hat{c}_{t+1}^b - \frac{1}{qc^b} \left(\hat{i}_t^b - \mathbb{E}_t \hat{\pi}_{t+1} - \hat{\zeta} + \mathbb{E}_t \zeta_{t+1} \right) \tag{C.63}$$

$$\hat{c}_t^s = \hat{c}_{t+1}^s - \frac{1}{qc^s} \left(\hat{i}_t^s - \mathbb{E}_t \hat{\pi}_{t+1} - \hat{\zeta} + \mathbb{E}_t \zeta_{t+1} \right) \tag{C.64}$$

$$c^b \hat{\pi}_t + c^b \hat{c}_t^b = \hat{\pi}_t \left(\chi y + b^b \right) + \chi y \, \hat{y}_t + b^b \hat{b}_t^b - \frac{b^b}{\pi} \hat{i}_{t-1}^b - \left(1 + i^b \right) \frac{b^b}{\pi} \hat{b}_{t-1}^b \tag{C.65}$$

$$- m^b (\hat{m}_t^b + \hat{\pi}_t) + (1 - \gamma) \frac{m^b}{\pi} \hat{m}_{t-1}^b$$

$$\frac{\Omega''(m^b) m^b}{\Omega'(m^b)} \hat{m}_t^b = -qc^b \hat{c}_t^b - \frac{i^b + \gamma - 1}{i^b + \gamma} \hat{i}_t^b \tag{C.66}$$

$$\frac{\Omega''(m^s) m^s}{\Omega'(m^s)} \hat{m}_t^s = -qc^s \hat{c}_t^s - \frac{i^s + \gamma - 1}{i^s + \gamma} \hat{i}_t^s \tag{C.67}$$

$$c\hat{b}c_t = \frac{R}{cbc} \hat{R}_t + \frac{m}{cbc} \hat{m}_t + \frac{m^b}{cbc} \hat{m}_t^b + \frac{m^s}{cbc} \hat{m}_t^s \tag{C.68}$$

$$\hat{\pi}_t + c\hat{b}c_t = \frac{1}{\pi} c\hat{b}c_{t-1} + \frac{R}{cbc\,\pi} \left(\hat{i}_{t-1}^r + i^r \hat{R}_t \right) - \frac{\tau^s}{cbc} \left(\hat{\tau}_t^s + \hat{\pi}_t \right) \tag{C.69}$$

$$\hat{\pi}_t = \kappa \hat{y}_t + \beta \mathbb{E}_t \hat{\pi}_{t+1} \tag{C.70}$$

$$\hat{i}_t^b = \hat{i}_t^s + \hat{\omega}_t \tag{C.71}$$

$$\hat{\omega}_t = \frac{i^b - i^s}{1 + i^b} \left((\nu - 1) \hat{b}_t^b - \nu \hat{\bar{b}}_t - \iota \hat{z}_t \right) \tag{C.72}$$

$$\hat{i}_t^s + \hat{z}_t = \frac{\chi b^b}{(1 + i^s)\,z} \left(\hat{i}_t^b - \hat{i}_t^s + \left(i^b - i^s \right) \hat{b}_t^b \right) - \frac{R}{(1 + i^s)\,z} \left(\hat{i}_t^s - \hat{i}_t^r \right) \tag{C.73}$$

$$- \frac{m}{(1 + i^s)\,z} \left(\hat{i}_t^s + (i^s + \gamma)\,\hat{m}_t \right) - \frac{\Gamma}{(1 + i^s)\,z} \hat{i}_t^s$$

$$- \frac{\Gamma_z}{\iota} \left(\nu \left(\hat{b}_t^b - \hat{\bar{b}}_t \right) + \iota \hat{z}_t \right) - \frac{m\,(m - \overline{m})}{z} \hat{m}_t$$

$$\hat{R}_t = \frac{1}{(1 + i^s) R} \left((\overline{R} - 1) \hat{i}_t^s + \hat{i}_t^r \right) - \hat{i}_t^s \tag{C.74}$$

$$\hat{m}_t = \frac{m - \bar{m}}{m} \frac{1 - i^s - \gamma}{i^s + \gamma} \hat{i}_t^s \tag{C.75}$$

$$\hat{i}_t^r = \hat{r}_t^n + \phi_\Pi \hat{\pi}_t + \phi_Y \hat{y}_t \tag{C.76}$$

$$\hat{i}_t^s = \max \left\{ -\gamma \beta^s - (1 - \beta^s), \hat{i}_t^r \right\} \tag{C.77}$$

C.3   Calibration and numerical simulation of a debt-deleveraging shock

Calibration

We pick the size of the preference shock to generate an approximately 4.5 percent drop in output on impact.[17] This reduction in output is chosen to roughly mimic the average reduction in real GDP in Sweden, Denmark, Switzerland and the Euro Area in the aftermath of the financial crisis, as illustrated in Figure C.1 in the Appendix C.1.[18] The drop in output in the US was of similar order. The persistence of the preference shock is set to generate a duration of the lower bound of approximately 12 quarters. We choose parameters from the existing literature whenever possible. We target a real borrowing rate of 4 %[19] and a real deposit rate of 1.5 %, yielding a steady state credit spread of 2.5 %. The preference parameter q is set to 0.75, which generates an intertemporal elasticity of substitution of approximately 2.75, in line with Curdia and Woodford (2011). We set the proportional storage cost to 0.01, yielding an effective lower bound of - 0.01 %. This is consistent with the deposit rate being bounded at zero for most types of deposits, with the exception of slightly negative rates on corporate deposits in some countries. We set $\overline{R} = 0.07$, which yields steady-state reserve holdings in line with average excess reserves relative to total assets for commercial banks from January 2010 and until April 2017.[20] We set $\overline{m} = 0.01$, implying that currency held by banks in steady state accounts for approximately 1.5 percent of total assets. This currency amount corresponds to the difference between total cash assets reported at US banks and total excess reserves from January 2010 until April 2017.

The parameter ν measures the sensitivity of the credit spread to private debt. We set ν so that a 1 % increase in private debt increases the credit spread by 0.12 %, as in Benigno, Eggertsson, and Romei (2014). Given the steady-state credit spread, $\bar{l}$ pins down the steady-state level of private debt. We choose $\bar{l}$ to target a steady state private debt-to-GDP ratio of approximately 95 percent, roughly in line with private debt in the period 2005 - 2015 (Benigno, Eggertsson, and Romei, 2014). The final parameter is ι. In our baseline scenario we set $\iota = 0.2$. While ι is not important for our main result that negative interest rates are not expansionary, it is important for determining the feedback effect from bank profits to aggregate demand. In Table 4.3 in the next section we show how the potentially contractionary effect of negative interest rates depends quantitatively on ι.

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[17]We pick the size of the debt deleveraging shock to generate a similar output reduction.

[18]Detrended real GDP fell sharply from 2008 to 2009, before partially recovering in 2010 and 2011. The partial recovery was sufficiently strong to induce an interest rate increase. We focus on the second period of falling real GDP (which occurred after 2011), as negative interest rates were not implemented until 2014-2015. Targeting a reduction in real GDP of 4.5 percent is especially appropriate for the Euro Area and Sweden. Real GDP fell by somewhat less in Denmark, and considerably less in Switzerland. This is consistent with the central banks in the Euro Area and Sweden implementing negative rates because of weak economic activity, and the central banks in Denmark and Switzerland implementing negative rates to stabilize their exchange rates.

[19]This is consistent with the average fixed-rate mortgage rate from 2010-2017. Series MORTGAGE30US in the St.Louis Fed's FRED database.

[20]We use series EXCSRESNS for excess reserves and TLAACBW027SBOG for total assets from commercial banks, both in the St.Louis Fed's FRED database.

All parameter values are summarized in Table C.1. Due to the occasionally binding constraint on i_t^s, we solve the model using OccBin (Guerrieri and Iacoviello, 2015) for the preference shock. For simplicity, we consider a cashless limit for the household's problem .[21]

Debt deleveraging shock

In this appendix, we show the dynamic transition of our model to an alternative shock, a debt deleveraging shock. Specifically, we consider a permanent reduction in the debt limit $\bar{l}_t$[22], a shock often referred to as a "Minsky Moment" (Eggertsson and Krugman, 2012). . The dynamic transition paths are shown in Figure C.4 A permanent reduction in the debt limit directly increases the interest rate spread, causing the borrowing rate to increase. The initial increase in the borrowing rate is substantial, due to the shock's impact on bank profits and the feedback effect via ι. In the frictionless case, the central bank can perfectly counteract this by reducing the reserve rate below zero. Given the bound on the deposit rate however, the central bank looses its ability to bring the economy out of a recession. Any attempt at doing so, by reducing the reserve rate below zero, only lowers bank profits and aggregate demand further.

In some respects this shock – with the associated rise in the borrowing rate – resembles more the onset of the financial crisis, when borrowing rates (in some countries) increased. The preference shock considered in the main body of the text is more consistent with the situation further into the crisis, when both deposit and lending rates were at historical low levels (perhaps reflecting slower moving factors such as those associated with secular stagnation, see Eggertsson and Mehrotra (2014)). From the point of view of this paper however, it makes no difference which shock is considered in terms of the prediction it has for the effect of negative central bank rates. In both cases, the policy is neutral when there is no feedback from bank profits, and contractionary when there is such a feedback.

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[21] There are no additional insights provided by allowing households to hold money in the numerical experiments, even if this feature of the model was essential in deriving the bound on deposits.

[22] A temporary shock to bank's intermediation costs yield qualitatively similar results.

Parameter	Value	Source/Target
Inverse of Frisch elasticity of labor supply	$\eta = 1$	Justiniano et.al (2015)
Preference parameter	$q = 0.75$	Yields IES of 2.75 (Curdia and Woodford, 2011)
Share of borrowers	$\chi = 0.61$	Justiniano et.al (2015)
Steady-state gross inflation rate	$\Pi = 1.005$	Match annual inflation target of 2%
Discount factor, saver	$\beta^s = 0.9901$	Annual real savings rate of 1.5 %
Discount factor, borrower	$\beta^b = 0.9963$	Annual real borrowing rate of 4 %
Probability of resetting price	$\alpha = 2/3$	Gali (2008)
Taylor coefficient on inflation gap	$\phi_\Pi = 1.5$	Gali (2008)
Taylor coefficient on output gap	$\phi_Y = 0.5/4$	Gali (2008)
Elasticity of substitution among varieties of goods	$\theta = 7.88$	Rotemberg and Woodford (1997)
Proportional storage cost of cash	$\gamma = 0.01$ %	Effective lower bound $\underline{i}^s_t = -0.01\%$
Reserve satiation point	$\overline{R} = 0.07$	Target steady-state reserves/total assets of 13 %
Money satiation points	$\overline{m} = 0.01$	Target steady-state cash/total assets of 1.5 %
Marginal intermediation cost parameters	$\nu = 6$	Benigno, Eggertsson, and Romei (2014)
Level of safe debt	$\bar{l} = 1.3$	Target debt/GDP ratio of 95 %
Link between profits and intermediation costs	$\iota = 0.2$	1 % inc. in profits $\approx$ 0.01 % red. in credit spread

Shock	Value	Source/Target
Preference shock	2.5 % temporary decrease in ζ_t	Generate a 4.5 % drop in output on impact
Persistence of preference shock	$\rho = 0.9$	Duration of lower bound of 12 quarters
Debt deleveraging shock	50 % permanent reduction in $\bar{l}$	Generate a 4.5 % drop in output on impact

Table C.1: Parameter values
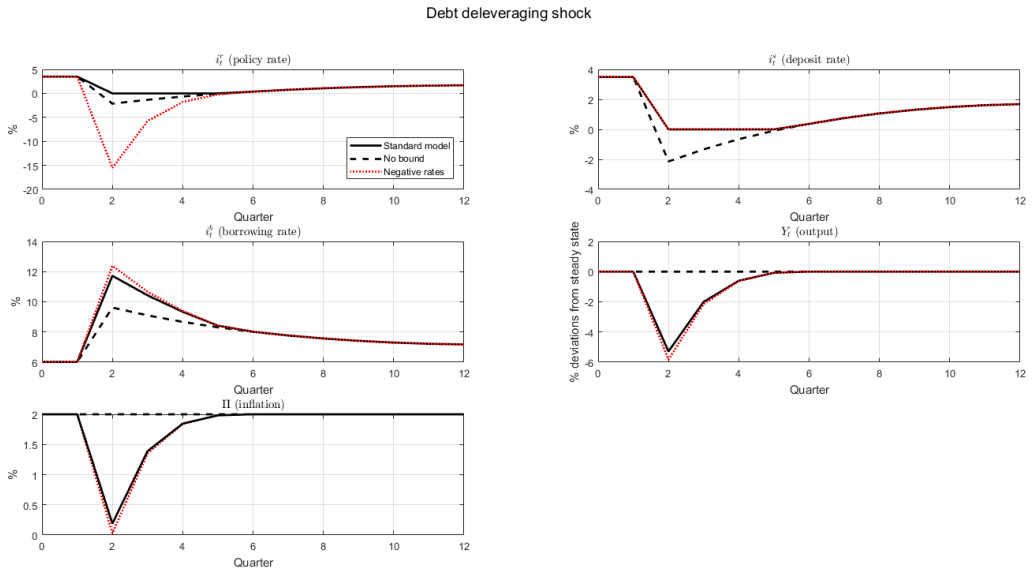
Debt deleveraging shock

Figure C.4: Impulse response functions following a debt deleveraging shock (a permanent reduction in $\bar{l}_t$), under three different models. S*tandard model* refers to the case where there is an effective lower bound on both deposit rates and the central bank's policy rate. *No bound* refers to the case where there is no effective lower bound on any interest-rate. *Negative rates* refers to the model outlined above, where there is an effective lower bound on the deposit rate but no lower bound on the policy rate.

Appendix D

Appendix to Chapter 5

D.1 Additional figures

Figure D.1: Placebo Test - Change in log(Capital Ratio) for low and high capitalized banks.

Figure D.2: Interest Rates. Left panel: Distribution of backed out interest rates. Right panel: Aggregate backed out interest rates and aggregate interest rates on corporate lending from Statistics Norway
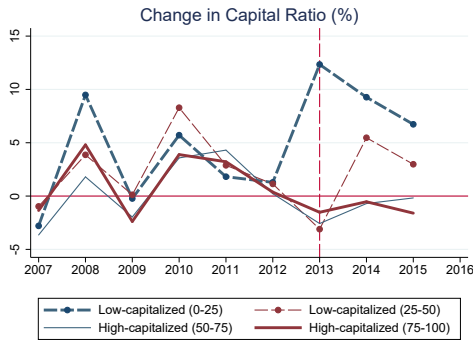

Figure D.3: Capital Ratios. Banks are divided into groups based on their 2012 capital ratios. Change in capital ratios for banks in quartile 1 (0th to 25th percentile), quartile 2 (25th to 50th percentile), quartile 3 (50th to 75th percentile) and quartile 4 (75th to 100th percentile).

D.2   Frictions in firm-bank lending

In this appendix, we document two quantitatively important frictions in firm bank lending. First, there is inertia in bank lending, meaning that firms tend to borrow from their insider bank. Second, there is geographical matching, meaning that firms are more likely to borrow from a local bank.

If past bank relationships have no predictive power on future bank relationships, the probability of borrowing from any bank is constant across firms. We define *random switching* as the case in which current lending relationships between bank i and firm j, L_{ij}, are independent of past lending relationships $L_{ij,-1}$. Given random switching, the probability that firm j switches to a new bank is given by $1 - \Pr(L_{ij}|L_{ij,-1}) = 1 - \Pr(L_{ij}) = 1 - M_i$, where M_i denotes the market share of bank i. To obtain the *observed* switching probability we calculate the number of firms obtaining new loans from a *new* bank relative to the number of firms obtaining new loans from *any* bank. That is, $\Pr(\text{Switch})^{\text{observed}} = \frac{\# L_{ij}|\neg L_{ij,-1}}{\# L_{ij}}$, where L_{ij} denotes a new loan from bank i to firm j in the current period.

The left panel of Figure D.4 shows the calculated random switching probabilities and the observed switching probabilities. The random switching probabilities vastly exceed the observed switching probabilities, suggesting that previous bank relationships do have power in predicting future bank lending. The random switching probability exceeds 80 percent, compared to an observed switching probability of somewhere between 10 and 20 percent.

To formally test for firm-bank stickiness, we restrict the sample to firms which are acquiring a new loan in a given period. We then estimate how the likelihood of obtaining a loan from bank i depends on already having outstanding debt with bank i.[1] That is, we run the regression specified in equation (D.1). The dependent variable I_{ij} is equal to one if firm j obtains a new loan from bank i, and zero otherwise. The independent variable $\text{Bank}_{ij,-1}$ is equal to one if firm j had outstanding debt at bank i in the previous period, i.e. if bank i is an insider bank to the firm. Based on the low degree of observed switching documented in Figure D.4 we expect a positive and large $\hat{\beta}$.

$$I_{ij} = \alpha + \beta \text{Bank}_{ij,-1} + \epsilon_{ij} \tag{D.1}$$

The regression results are reported in Table D.1. The second column controls for bank market size by year, and gives an estimate of β equal to 0.88. Hence, the estimated probability of switching banks conditional on taking up a new loan is just above ten percent.[2] This is somewhat lower than in Chodorow-Reich (2014), which is not surprising as our sample consists of smaller firms which have been documented to have stronger attachments to their insider banks (Ongena and Smith, 2001).

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[1] We define previous banking relationships based on debt, which seems to be the common practice in the literature. However, one could imagine that also deposits could be included in the definition.

[2] We follow the literature in using the term *switching* to capture both firms that actually switch banks, as well as firms that add a new bank connection without terminating the previous one.

	(1)	(2)
	L_{ij}	L_{ij}
$Bank_{ij,-1}$	0.892***	0.880***
	(123)	(104)
Bank FE	-	yes
Observations	6,470,744	6,470,744

t statistics in parentheses. Std. err. clustered at bank $\times$ year level

* $p < .10$, ** $p < .05$, *** $p < .01$

Table D.1: Relationship Lending. Regression results from estimating equation (D.1).
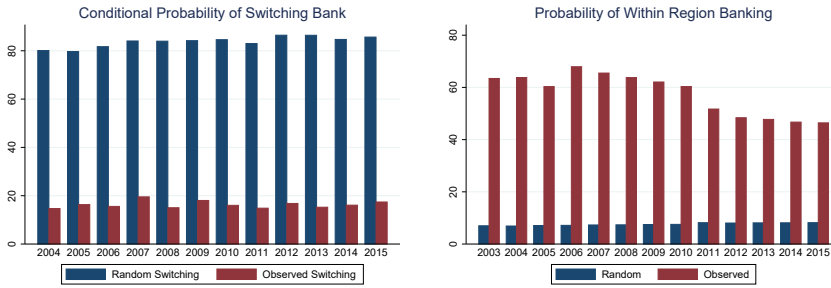

Figure D.4: Observed and Random Switching Probabilities

To evaluate whether spatial frictions are important in our data, we calculate the observed probability that a firm j borrows from a bank i in its own region. Let $C_{ij} = 1$ if the region of firm j coincides with the region of its insider bank i, and zero otherwise. We define the observed matching as the average matching occurrence across firms $\Pr(\text{match})^{\text{observed}} = \bar{C}_{ij}$. We compare this to a *random matching* probability, calculated under the assumption that spatial locations have no predictive power on firm-bank lending. Given random matching, the probability that a firm i borrows from a bank in its region is simply given by the sum of the market shares M_i of all banks located in its region, i.e. $\Pr(\text{match}_j)^{\text{random}} = \sum_{i \in \text{match}_i} M_i$. The aggregate matching probability under random matching is simply the average across all firms in our sample. Hence, the random matching probability depends on the spatial distribution of bank market shares and the spatial distribution of firms. The right panel of Figure D.4 illustrates the degree of county matching in our sample, as well as the counterfactual matching under the assumption of random matching. On average, around 55 percent of lending relationships are within-county. This compares to a predicted matching of less than 10 percent if geography was irrelevant

D.3   Aggregate corporate credit supply

In order to back out the reform-induced increase in capital ratios and credit supply we need to make use of some additional assumptions. First, we will abstract from any general equilibrium effects. Our cross-sectional results would not capture such effects. Second, we need an extra assumption in order to go from relative changes to aggregate changes. That is, we know that low-capitalized banks increased their capital ratios and reduced their credit growth *relative* to high-capitalized banks, but we do not know how these changes were distributed. For example, one could make the case that high-capitalized banks were unaffected by the reform, while low-capitalized banks reacted to the reform by substantially reducing credit growth. However, one could also imagine high-capitalized banks picking up some of the slack resulting from the reduction in credit supply from low-capitalized banks. In this case, credit supply for both bank types will be affected. Hence, the correct way to translate our cross-sectional results into aggregate results depends on the degree of spillovers.

Formally assessing the degree of spillovers is challenging. It is likely to depend on, among other things, the spatial distribution of low-capitalized and high-capitalized banks, the importance of spatial barriers and the degree of relationship banking. While we find it plausible that there is some degree of spillovers, we argue that it appears to be of limited magnitude. This is based on three features of the data. First, while there is the same number of low-capitalized and high-capitalized banks by construction, the two bank types account for very different market shares. Because the largest banks in our sample are all low-capitalized, the group of low-capitalized banks account for roughly 90 percent of corporate lending volumes. This makes it practically difficult for the high-capitalized banks to absorb a quantitatively important share of the credit demand usually directed at low-capitalized banks.
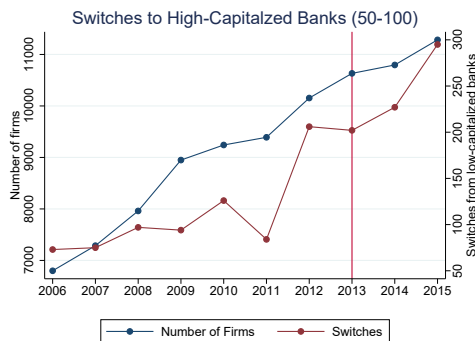

Figure D.5: Spillovers. Number of Firms Switching from Low-Capitalized Banks to High-Capitalized Banks

Second, our loan level panel data allows us to explicitly calculate the number of firms that switch from low-capitalized banks to high-capitalized banks per year. The result of such a calculation is captured by the red line in Figure D.5. Only between 50 and 250 firms switch from

low-capitalized banks to high-capitalized banks each year, reflecting the low combined market share of high-capitalized banks. The number is growing over time, following the growth in the total number of firms as captured by the green, dashed line.[3] While we do not observe the counterfactual evolution of switches in absence of the reform taking place, we see no break in the time trend post-reform.

Finally, any evidence of real effects would suggest that low-capitalized banks are not (fully) picking up the slack caused by reduced credit supply from low-capitalized banks. We documented in Section 5 that there is a negative impact on employment, suggesting that aggregate credit supply falls as a result of the reform. Although we believe the magnitude of spillovers to be limited, we calculate the aggregate credit supply effect under a range of different assumptions, some of which allow for substantial spillovers.

In order to back out the aggregate effect on credit supply we rely on one of the alternative assumptions listed below. We chose these assumptions to provide plausible upper and lower bounds for the aggregate impact on credit supply.

1. *Unaffected at the top*: In absence of the reform all banks would have changed their capital ratios by the same amount as high-capitalized banks

2. *Unchanged trends*: In absence of the reform low-capitalized and high-capitalized banks would have changed their capital ratios by their respective pre-reform trend levels

3. *Zero change*: In absence of the reform there would be no changes in capital ratios

First we assume that high-capitalized banks were unaffected by the reform. In this case we use the average change in capital ratios for high-capitalized banks as the counterfactual. That is, we assume that all banks would have changed their capital ratios by the same amount as high-capitalized banks in absence of the reform. Here we define high-capitalized banks to mean the 50 percent most highly capitalized banks, but we obtain similar results if we instead consider only the 25 or the 10 percent highest capitalized banks to be unaffected. Note that this counterfactual implies no spillovers, and so will provide us with an upper bound for the aggregate effect of the reform. Because we have data for several years prior to the reform, we can also calculate counterfactual changes in capital ratios based on pre-reform time trends. The challenge with this approach is that capital ratios have been increasing steadily since the financial crisis, partly due to expectations of higher capital requirements. Hence, assuming that banks would have continued on their pre-reform trends is likely to underestimate the effect of the reform. The aggregate impacts backed out under this assumption therefore provides a plausible lower bound for the effect of the reform. Finally, we also make use of an intermediate assumption, in which we assume that banks would have kept their capital ratios unchanged in absence of the reform. Both of the latter assumptions allow for substantial spillovers between bank types.

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[3]We do not know for certain what is causing the drop in switches from low-capitalized banks to high-capitalized banks in 2011. There was an unusually high number of mergers and acquisitions in 2010 and 2011, involving relatively large banks. Although we account for the direct effect of mergers, there might still be indirect effects that are showing up in our calculations.

The left panel of Figure D.6 depicts the observed and counterfactual changes in capital ratios. We calculate a weighted average change based on the market shares of high-capitalized and low-capitalized banks, as this is the most economically interesting outcome. Because all the market leaders are low-capitalized, this implies that low-capitalized banks receive a larger weight in the aggregated time series. Table D.2 reports the cumulative changes in capital ratios and credit supply from 2012 to 2015. Capital ratios increased by 12.5 percent from 2012 to 2015. This is captured by the solid blue line in the left panel of Figure D.6. Our counterfactual assumptions imply an increase in capital ratios over the same period of - 4.0 to 5.5 percent. The reform-induced increase in capital ratios is largest when we assume that high-capitalized banks were unaffected, and smallest when we assume unchanged time trends. Hence, even our most conservative assumption implies that the reform caused capital ratios to increase by an additional seven percentage points, or more than twice as much as in absence of the reform.

The credit supply effects are illustrated in the right panel of Figure D.6 and reported in Table D.2. From 2012 to 2015, observed credit supply increased by 8.6 percent. This is captured by the solid blue line in the right panel of Figure D.6. If capital ratios had behaved according to our counterfactual scenarios, the increase in credit supply would have been substantially larger, especially in the year immediately following the reform. Given the assumptions of high-capitalized banks being unaffected by the reform, credit supply would have increased by 39 percent over this three-year period. Given the assumption of zero change, credit supply would have increased by 31 percent. Finally, if we instead assume that low-capitalized and high-capitalized banks would have changed their capital ratios according to their respective pre-reform trends, credit supply would have increased by 24 percent from 2012 to 2015. Hence, even our most conservative assumption implies that the weighted average increase in credit supply in the three years following the reform would have been almost three times higher in absence of the reform.
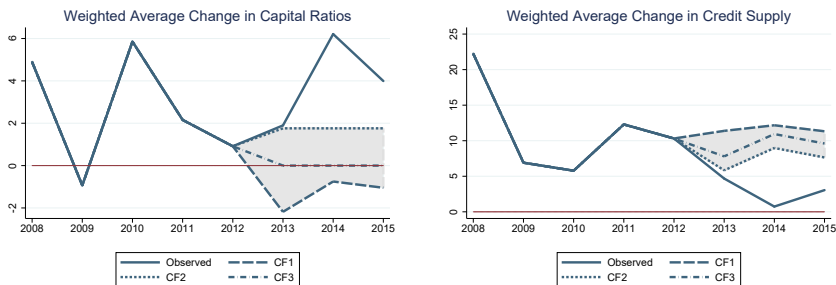

Figure D.6: Observed and Counterfactual Changes in Capital Ratios and Credit Supply

	Cumulative Change in Capital Ratios	Cumulative Change in Credit Supply
Unaffected at the top	- 4.0 %	39 %'
Zero change	0 %	31 %'
Unchanged trends	5.5 %	24 %'
Observed	12.5 %	8.6 %'

Table D.2: Cumulative Weighted Average Observed and Counterfactual Changes in Capital Ratios (%-change) and Credit Supply (symmetric %-change) from 2012 to 2015

Appendix E

Appendix to Chapter 6

E.1   EBA-banks

Name	
BNP Paribas	Intesa Sanpaolo
Banca Monte dei Paschi di Siena	Jyske Bank
Banca Popolare di Sondrio	Landesbank Berling Holding
Banco BPI	Lloyds Banking Group
Banco Bilbao Vizcaya	Nordea Bank
Banco Comercial Portugues	OTP Bank
Banco Popular Espanol	PKI Bank
Bank of Valletta	TSB Group Holdings
Barclays	Raiffeisen Bank
Caixa Bank	Royal Bank of Scotland
Credit Agricole	Skandinaviska Enskilda Banken
DNB	Societe Generale
Danske Bank	Swedbank
Deutsche Bank	Sydbank
Erste Group Bank	UniCredit
Espirito Santo Financial Group	Unione di Banche Italiane
HSBC Holdings	

Table E.1: EBA-banks in sample.

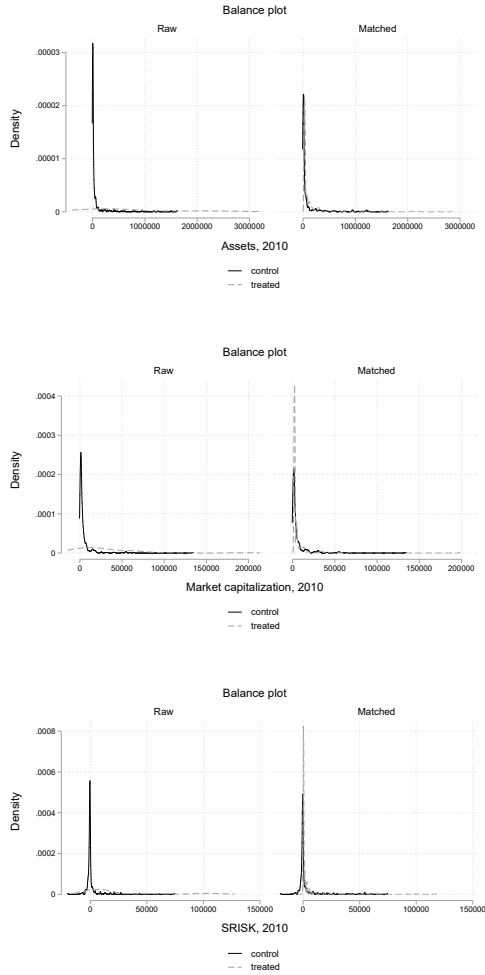## E.2   Covariate balance

Figure E.1: Covariate balance for EBA and non-EBA banks for the baseline matching strategy. Matching variables: End of 2009 total assets, and January 2010 market capitalization and SRISK.
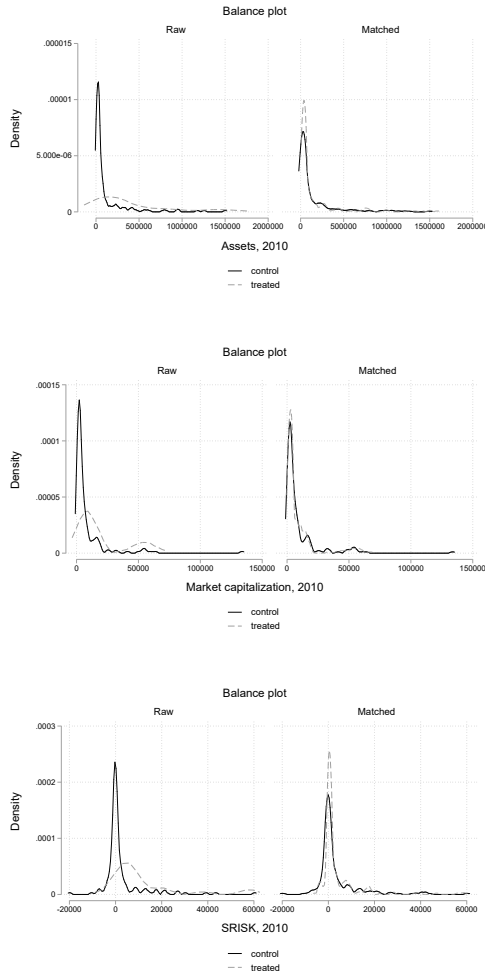
Figure E.2: Covariate balance for EBA and non-EBA banks for the overlap matching strategy. Matching variables: End of 2009 total assets, and January 2010 market capitalization and SRISK.

E.3   Robustness

This appendix reports the results from various robustness exercises. For brevity, only results using the flexible difference-in-differences is reported.

Controlling for PIIGS exposure

First, consider the full analysis on a non-GIIPS subsample.
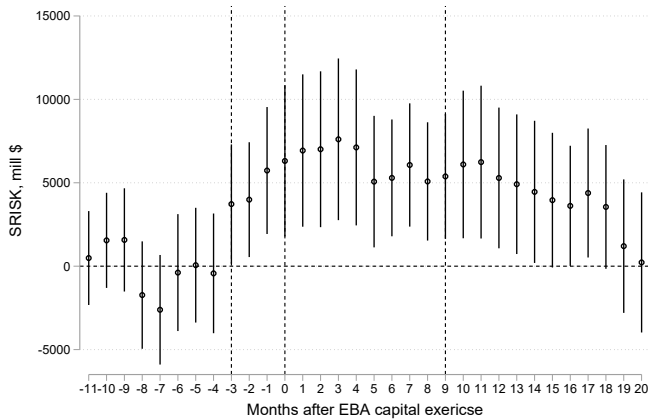
Figure E.3: Coefficients γ_k from regressing equation (6.1) with SRISK as dependent variable. Vertical bars are 95 % confidence intervals clustered at the bank level. October 2011 defined as period 0. Vertical lines correspond to the release of EBA stress test result, the actual introduction of heightened capital requirements in October 2011 and the first month after the EBA capital exercise (July 2012).

In Figure E.3 I plot the results from estimating equation (6.1) on the sample excluding banks from GIIPS-nations. As is clear, the pattern of increasing SRISK for EBA banks right at the onset of the EBA capital exercise is still prevalent.

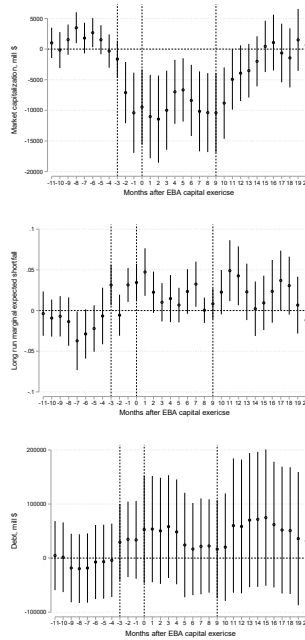Figure E.4: Coefficients γ_k from regressing equation (6.1) with market capitalization (left), LRMES (mid) and debt (bottom) as dependent variables. Vertical bars are 95 % confidence intervals clustered at the bank level. October 2011 defined as period 0. Vertical lines correspond to the release of EBA stress test result, the actual introduction of heightened capital requirements in October 2011 and the first month after the EBA capital exercise (July 2012)..

Next, in Figure E.4, I plot the results from estimating equation (6.1) on the sample excluding banks from GIIPS-nations using market capitalization (top panel), the long-run marginal expected shortfall (mid-panel) and debt (bottom panel) as dependent variables respectively. The pattern from the regressions on the main sample remains qualitatively unchanged. EBA banks in non-GIIPS countries faces a reduction in market capitalization, as well as an increase in the long-run marginal expected shortfall.

Overall, the results in this section suggests that the results outlined in the main body of the text is not driven by GIIPS banks but is also present for the remaining EBA-banks.

Adding control variables

The regressions in the main body of the text did not include any controls. In this section, I estimate an augmented version of 6.1, i.e I estimate

$$Y_{i,t} = \alpha + EBA_i + \sum_{k \neq \text{january } 2010} \beta_k \mathbf{1}_{t=k} + \sum_{k \neq \text{january } 2010} \gamma_k \left(\mathbf{1}_{t=k} \times EBA_i \right) + \boldsymbol{\delta}' \boldsymbol{X_{i,t}} + \epsilon_{i,t} \quad \text{(E.1)}$$

where $\boldsymbol{X_{i,t}}$ is a vector of control variables including the January 2010 values of total assets, leverage, long-run marginal expected shortfall and country fixed-effects. The results are shown in Figure E.5 and Figure E.6. While the point estimates are slightly higher compared to the case without controls, the qualitative differences from the analysis in the main body of the paper are zero.

Figure E.5: Coefficients γ_k from regressing equation (E.1) with SRISK as dependent variable. Vertical bars are 95 % confidence intervals clustered at the bank level. October 2011 defined as period 0. Vertical lines correspond to the release of EBA stress test result, the actual introduction of heightened capital requirements in October 2011 and the first month after the EBA capital exercise (July 2012).
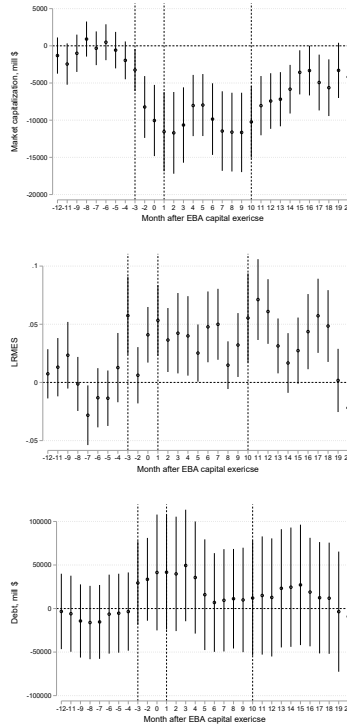
Figure E.6: Coefficients γ_k from regressing equation (E.1) with market capitalization (top), LRMES (mid) and debt (bottom) as dependent variables. Vertical bars are 95 % confidence intervals clustered at the bank level. October 2011 defined as period 0. Vertical lines correspond to the release of EBA stress test result, the actual introduction of heightened capital requirements in October 2011 and the first month after the EBA capital exercise (July 2012).

Adding country $\times$ year fixed effects

Next, I estimate

$$Y_{i,t} = \alpha + EBA_i + \sum_{k \neq \text{january 2010}} \beta_k \mathbf{1}_{t=k} + \sum_{k \neq \text{january 2010}} \gamma_k \left(\mathbf{1}_{t=k} \times EBA_i \right) + \sum_{\tau = 2010,2011,...} \kappa_{j(i)} \delta_\tau + \epsilon_{i,t}$$

$$(\text{E.2})$$

where $\kappa_{j(i)}$ is country-specific fixed effects and δ_τ is yearly fixed effects. For brevity, I only report the results using systemic risk as the dependent variable. The results are largely unchanged and shown in Figure E.7
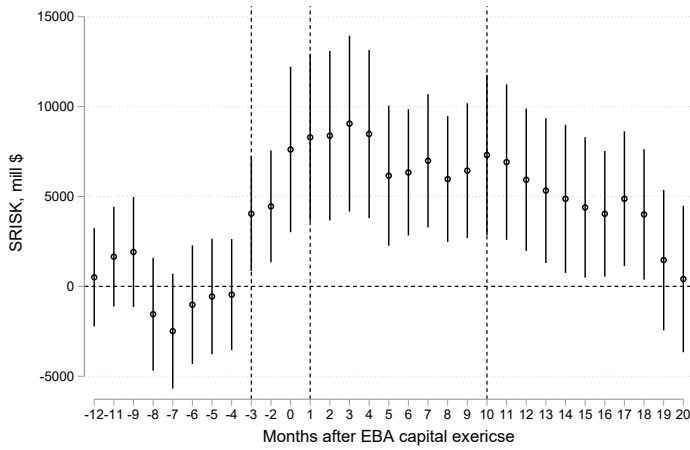
Figure E.7: Coefficients γ_k from regressing equation (E.2) with SRISK as dependent variable. Vertical bars are 95 % confidence intervals clustered at the bank level. October 2011 defined as period 0. Vertical lines correspond to the release of EBA stress test result, the actual introduction of heightened capital requirements in October 2011 and the first month after the EBA capital exercise (July 2012).

Placebo test

A different way of ensuring that the divergence between EBA banks and non-EBA banks during the capital exercise is due to increased capital requirements and not the sovereign debt crisis, is to compare the evolution of systemic risk for the two groups at the onset of the sovereign debt crisis. In this section, I therefore estimate

$$Y_{i,t} = \alpha + EBA_i + \sum_{k \neq \text{december 2009}} \beta_k \mathbf{1}_{t=k} + \sum_{k \neq \text{december 2009}} \gamma_k \left(\mathbf{1}_{t=k} \times EBA_i \right) + \epsilon_{i,t} \qquad \text{(E.3)}$$

For brevity, I only report the results using systemic risk as the dependent variable. The results are largely unchanged and shown in Figure E.8
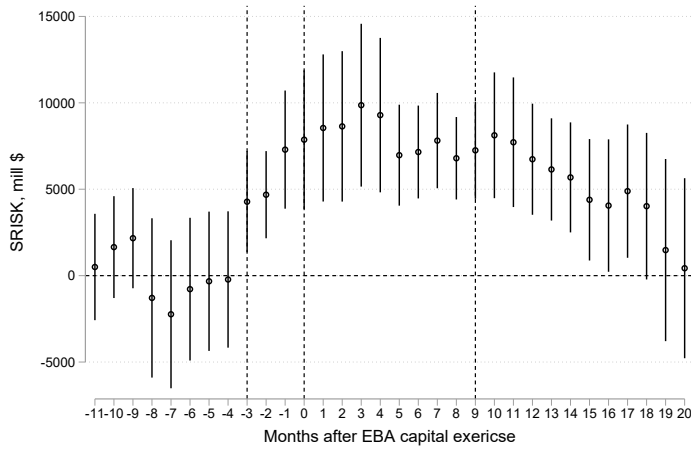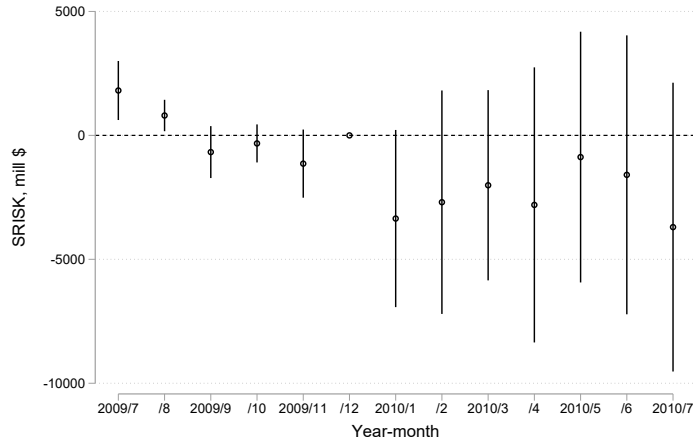
Figure E.8: Coefficients γ_k from regressing equation (E.3) with SRISK as dependent variable. Vertical bars are 95 % confidence intervals clustered at the bank level.

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