

Essays on Bank Runs, Contagion and Systemic Risk

by

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A handwritten signature in cursive script, reading "Douglas Gale", positioned above a horizontal line.

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DEDICATION

To my parents Esin and Aktan Yorulmazer and to my wife Gulperi Furtun.

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ABSTRACT

The first essay investigates the role of herd behavior of depositors as a source of bank runs. I show that eliminating bank runs completely has some costs. Furthermore, a deposit contract that allows for runs can achieve higher levels of depositor welfare than a contract that completely eliminates them. Since early liquidation of bank's assets is costly, a central bank that acts as a lender of last resort alleviates some of the costs associated with bank runs. Yet it cannot prevent runs on healthy banks in the absence of perfect information about the bank's asset quality. In those cases, a deposit contract, even with liquidity support from the central bank, cannot achieve the first-best efficient outcome. Any effort to give market discipline a stronger role in achieving financial stability should be accompanied by transparency and disclosure of information.

The second essay investigates the factors that determine the severity of bank runs and points out possible policies that might dampen them. We show that the more information economic agents can expect to have about an ongoing financial crisis, the more willing they are to restrain themselves in withdrawing their funds from banks once a crisis actually occurs. We demonstrate that deposit insurance, even of a limited type, can also help to diminish the severity of bank runs. We also find that the presence of insiders is welfare

increasing in the sense that when such insiders exist, subjects tend to withdraw their money.

The third essay investigates the interaction of banks in choosing the correlation in their investment portfolios and the implications of these choices on systemic risk. When bank loan returns have a systematic factor, the failure of one bank conveys adverse information about this systematic factor and increases the cost of borrowing for the surviving banks. Given their limited liability, banks herd ex-ante and undertake correlated investments to increase the likelihood of joint survival. If the depositors of a failed bank can migrate to the surviving banks, then herding incentives are mitigated and this gives rise to a pro-cyclical pattern in the correlation of bank loan returns.

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Chapter 1

Herd Behavior, Bank Runs and Information Disclosure

1.1 Introduction

Throughout their history, banks have been subject to runs. It is a well-known fact that banks have illiquid assets and liquid liabilities. This maturity mismatch makes banks vulnerable to runs if depositors become worried about the bank's asset quality and demand the return of their savings.

Although financial crises including bank runs are no longer a matter of concern in some parts of the world, the reality is that banking crises are still a constant feature of economies for a majority of the countries. Lindgren, Garcia and Saal (1996) show that during the period 1980-96, of the 181 IMF member countries, 133 experienced significant banking problems. Such problems affected developed, as well as developing and transitional countries¹ and had significant costs as documented by many studies².

Since the emergence of banks, supervision and regulation of the industry evolved as government and private responses to banking panics. The studies on the issue date back to Thornton (1802) that works on optimal central bank policies for lending in times of distress. Over the two centuries since Thornton (1802), many policies have been developed to prevent and manage banking

¹For example, over the past 25 years banking crises have hit such developed countries as Finland (1991-93), Norway (1988-92), Japan (1992-present), Spain (1977-85), and Sweden (1991) and have recently troubled such developing countries as Russia (1998), Brazil (1999), Turkey (2000) and (2001) and Argentina (2001), and various countries in Asia (1997-98).

²See Lindgren, Garcia and Saal (1996), Caprio and Klingebiel (1996), Lindgren et.al. (1999), Alexander et.al. (1997), Sundararajan and Baliño (1991), Hoggarth, Reis and Saporta (2001).

panics: suspension of convertibility, lender of last resort practices, deposit insurance, risk-based capital requirements, to cite a few. In light of the recent experiences, it is clear that the debate on these issues has not come to an end yet.

In his classic, *Lombard Street*, Bagehot (1873) argues that during times of panic, transparency on management of the crisis may reduce uncertainty and may have a calming effect on financial markets. In Bagehot's own words:

“If people could be really convinced that they could have money if they wait a day or two, and that utter ruin is not coming, most likely they would cease to run in such a mad way for money. Either shut the Bank (of England) at once and say it will not lend more than it commonly lends, or lend freely, boldly, and so that the public may feel you mean to go on lending. To lend a great deal, and yet not give the public confidence that you will lend sufficiently and effectually, is the worst of all policies.”

In this paper, I concentrate on the role of information externalities and herd behavior of depositors as a source of bank runs and, consistent with Bagehot's advice, suggest that transparency and disclosure of information on banks' soundness and management of the crisis can alleviate and eliminate some of the problems related to bank runs.

In doing so, I search for answers to some important questions, that are closely related with the stability of the banking system, such as:

- Can information externalities and herd behavior of depositors trigger bank runs?
- What are the costs of preventing these types of bank runs?
- Does optimal deposit contract allow for bank runs even when they can be generated by herd behavior of depositors and can be on healthy banks?
- In the presence of noisy private information, can a deposit contract, even with liquidity support³ from the central bank, achieve the first-best efficient outcome with public information?

When we look at the literature, we see that the bank run models have some common features. Most of them are static two-period equilibrium based models with a continuum of agents played in the simultaneous form. But Brunnermeier (2001) makes an important observation on the bank runs literature: “Although withdrawals by deposit holders occur sequentially in reality, the literature typically models bank runs as a simultaneous move game⁴”. With static models, we cannot analyze the dynamics of bank runs and we cannot

³In this paper, liquidity support will be only against good collateral. Therefore, it is not a bailout of the bank. See Section 6 for a detailed discussion.

⁴A few exceptions where depositors move sequentially would be Chen (1999), Green and Lin (2003) and Schotter and Yorulmazer (2003). Chen (1999) extends the Diamond and Dybvig (1983) model to multiple banks and allows for interim revelation of information about some banks’ performance. A sufficient number of bank failures results in pessimistic expectations about the general state of the economy and leads to runs on the remaining banks. This is a model with multiple banks that explains possible channels for contagion. In my model, there is only one bank. Therefore, my set up is not suitable to study contagion.

answer some of the questions I address. For these reasons, I diverge from these common features of bank run models.

In this paper, I build a model similar to the models of Diamond and Dybvig (1983) and Allen and Gale (1998) (DD and AG, respectively, from now on) but this is a dynamic model of bank runs where depositors move sequentially rather than simultaneously. This allows me to investigate the role of information externalities and herd behavior of depositors as a source of banking panics. The important feature of the model is that in an interim stage, depositors receive noisy private signals about the bank's asset quality and observe the actions of other depositors who move before them⁵. Since these signals are noisy, information revealed by the actions of depositors have value for other depositors. Depositors update their beliefs on the basis of these actions and their own private signals. A few number of withdrawals can lead depositors to withdraw even when they have a favorable signal about the prospects of the bank's investments. Hence, herd behavior of depositors can trigger a run on a healthy bank.

Early liquidation of bank's assets is costly, so the bank may choose a deposit contract that completely eliminates runs. To be able to do so, the bank has to promise a small return for those who want to withdraw early so that even

⁵To capture this, I use a very similar structure to the discrete signals model of Bikhchandani, Hirshleifer and Welch (1992).

a depositor who has observed a bad signal about the bank's prospects chooses not to withdraw. This will undermine the insurance provided by the deposit contract against a liquidity shock and is an important trade-off the bank needs to consider in choosing the deposit contract. I show that for a significant set of parameter values, it is optimal to allow for runs even if they can be generated by herd behavior of depositors and can be on healthy banks.

In the first-best efficient outcome with public information, when the bank cannot pay everybody the promised amount, the optimal arrangement is to distribute all the available funds equally among all depositors. But when bank runs are eliminated, early depositors will get their promised amount and if the return from the bank's investments is low, late depositors will get very little. This is another cost of eliminating runs completely the bank takes into account in choosing the optimal deposit contract (see AG for a detailed analysis).

In the bank runs literature, there are two main views about what triggers bank runs. One view states that bank runs are self-fulfilling phenomenon generated by "sunspots" as in the pioneering work of DD. They show that a deposit contract can give the optimal allocation by providing depositors insurance against uncertainty about their liquidity needs. If nobody thinks that there will be a run on the bank, only depositors with urgent liquidity needs withdraw early and there is no bank run. But, if depositors think that other depositors will withdraw their money, it is optimal for them to do so since there

will not be anything left for them if they do not withdraw. This is the Pareto inferior bank run outcome. Sunspots determine which of these self-fulfilling outcomes will occur.

Another view is that bank runs are natural consequences of the business cycle and they are information based. Gorton (1988) and Calomiris and Gorton (1991) empirically show that the banking crises in US in the late 19th and early 20th century are actual consequences of the business cycle and they are information driven.

In this paper there are both payoff and information externalities⁶ allowing me to combine some features of these two main views of bank runs in one model⁷. In my model, bank runs are triggered by the withdrawal decisions of a few number of depositors, revealing that they have adverse news about the bank's performance. This makes bank runs information driven. Yet, because of payoff and information externalities, once a run is triggered, it is optimal for everyone else to join the run even if they had good news about the bank's asset quality initially. Since depositors have noisy private signals, runs can be on healthy banks. Saunders and Wilson (1996) provides historical evidence of

⁶In many situations we observe both of these externalities in action but we have very few models studying this. Some would be Neeman and Orosel (1999), Dasgupta (2000) and Yorulmazer (2003).

⁷Though I have payoff externalities, the real reason that triggers a run is the information externalities. When the public belief about bank's prospects fall below a threshold, a run is triggered. This is a situation similar to the one sketched in Allen and Morris (2001). But with the help of payoff externalities, I show that once a run is triggered, everybody will join (see footnote 29).

runs on healthy banks, as I will later discuss in detail.

Here, I concentrate on some particular equilibria of the model which I find to be the most interesting⁸. There may be other equilibria, where “everybody runs” being a likely candidate. Since this is a dynamic game with information externalities, the public belief about the prospects of the bank evolves during the play of the game. When the public belief falls below a threshold, it is a dominant strategy to withdraw which makes a bank run the unique outcome from then on. When the public belief is above that threshold, “everybody runs” equilibrium can be eliminated by a constraint added to the deposit contract as long as the utility from receiving nothing from the bank is not extremely low⁹.

There are models with unique equilibrium to the bank run game in the literature but their features differ from my model. Some of these share the limitations of the models mentioned before. Therefore they are not appropriate models for the purposes of this paper. Following is a discussion of these studies and my model’s differences from them.

Green and Lin (2001), using a finite-player version of DD, develop a direct mechanism that implements the ex-ante efficient allocation as a unique

⁸Postlewaite and Vives (1987) and Chari and Jagannathan (1988) build models of incomplete information with a unique Bayesian equilibrium that has a positive probability of bank runs.

⁹See footnote 29 for a similar discussion.

outcome even when the bank uses the sequential-service constraint. In their model, aggregate uncertainty stems from the proportion of depositors that are subject to the liquidity shock. The return from the risky asset is constant. In my model, the return from the risky asset is random and this is the source of aggregate uncertainty. Their mechanism, under the sequential service constraint, pays different amounts to depositors who want to withdraw early, depending on the position they arrive the bank. This type of arrangement is not feasible in my contract space: depositors are treated equally in my model.

Goldstein and Pauzner (2002) use the equilibrium selection method¹⁰ introduced by Carlsson and van Damme (1993) and find a unique equilibrium in which fundamentals determine whether a bank run will occur or not. But they have a continuum of agents and the bank run game is played in the simultaneous form. With their set up, it may not be possible to answer some of the questions my paper is interested in such as the role of information externalities and herd behavior of depositors as a source of bank runs. Also, Saunders and Wilson (1996) and Park (1991) empirically document runs on healthy banks which is in contrast with the predictions of their model.

Some studies show that deposit contracts that are subject to bank runs are optimal arrangements and provide efficient outcomes. But in those models,

¹⁰Morris and Shin (2001) is an excellent article on the theory and the applications of global games including applications on bank runs. Morris and Shin (1998) uses the same technique to find unique equilibrium in a model of currency attacks.

information about banks' asset quality is perfect, and is public observed (AG) or revealed through the actions of *insiders*, who are perfectly informed about the performance of their bank (Calomiris and Kahn (1991)).

Calomiris and Kahn (1991) show that the deposit contract is the optimal arrangement even though it might create opportunity for bank runs and costly liquidation. The rationale behind this argument is that depositors can monitor their banks, which can act against their interest, by liquidating their funds. The event that triggers a run is the withdrawal decisions of the insiders.

Allen and Gale (1998) builds a model consistent with the empirical evidence of Gorton (1988) and Calomiris and Gorton (1991) that banking panics are related with the business cycle and are not the result of sunspots. They show that bank runs allow efficient risk sharing between early and late withdrawing depositors and allow banks to hold efficient portfolios. When runs carry costs due to early liquidation of assets, the first-best efficient outcome can be achieved by liquidity support from the central bank. In their model, the asset quality of the bank is realized and publicly observed in an interim period. This is crucial for the deposit contract, with liquidity support of the central bank, to achieve the first-best efficient outcome.

In contrast with the models discussed above, some studies provide empirical evidence for runs on healthy banks. For example, Saunders and Wilson (1996) examine deposit flows in 163 failed and 229 surviving banks over the Depression

era of 1929-1933 in US. In the years 1929 and 1933, they find evidence of “flight to quality” where withdrawals from failed banks were associated with deposit increases in surviving banks. However, they observe a decrease in deposits in both failed and surviving banks for the period of 1930-32. During this time, healthy banks experienced runs, too.

In another study, Park (1991)¹¹ looks at banking panics in US history and empirically shows that the government or banks stopped panics mainly by providing information on banks’ solvency rather than liquidity¹². He compares different arrangements used to manage and prevent banking panics according to their information provision and concludes that the arrangements that provided information on banks’ solvency were successful while those that provided only liquidity failed. He examines three different arrangements: equalization of reserves, clearing house loan arrangements and suspension of payments.

Clearing House loan certificates were acquired by banks by depositing qualifying assets with the Clearing House Association and they were used in inter-bank settlements. They prevent costly liquidation of assets and improve bank’s liquidity position. Since they were provided only when the Clearing House Association decided that the bank has enough assets to back them up, they also

¹¹Gorton (1985), Gorton and Mullineaux (1987) and Gorton and Huang (2002) document similar experiences. Sprague (1910) is an excellent source for banking crises in US under the national banking system.

¹²For an excellent survey on the role of “lender of last resort” in crisis management, see Freixas, Giannini, Hoggarth and Soussa (1999).

served the purpose of providing information that the bank was healthy.

Equalization of reserves was basically pooling all legal reserves of Clearing House Association member banks in an emergency and granting member banks equal access to the pooled resources. While equalization of reserves enhanced liquidity in the bank under attack, it did not provide any information on bank's asset quality. Because of this lack of information, equalization of reserves was ineffective in preventing runs when used in the 1873 crisis. Instead, stability of the banking system was established by using Clearing House loan certificates.

Suspension of payments was another arrangement used to manage banking panics. Their major role was to provide information rather than liquidity. Suspensions were always followed by thorough examination of the banks' assets. While banks with solvency problems were liquidated, solvent banks were reopened. This selective reopening procedure assured the public that the reopened banks were healthy. As a result of this, runs on reopened banks did not recur in most cases.

The results of this paper are in parallel with the empirical evidence discussed. In this model, while liquidity support alleviates the costs of early liquidation, it cannot prevent runs on healthy banks. The policy measure that will prevent these type of runs is the disclosure of information on the bank's soundness and management of the crisis. A deposit contract can achieve the first-best efficient outcome only in the presence of perfect information about

the banks' performance. In that sense, my results are complementary to the findings of the studies that suggest that a deposit contract, with liquidity support from the central bank, can achieve the first-best efficient outcome. In this paper, I argue that, while liquidity support is necessary, it is not sufficient in achieving the first-best efficient outcome. It has to be accompanied by transparency and disclosure of information on banks' soundness and management of crises.

This paper makes important suggestions on the policy side. In my model, deposit insurance can prevent runs and since early liquidation is costly, this can be welfare improving. But it is a well-known fact that in the presence of full insurance, depositors do not have any incentive to differentiate between sound and unsound banks. In such an environment, weak banks do not have any difficulty in attracting deposits. This creates an opportunity for moral hazard on banks' side that can cause adverse effects on the stability of the banking system.

Financial regulators and policy makers have been looking for alternatives for full deposit insurance (see Bhattacharya, Boot and Thakor (1998) for a comprehensive survey). Giving a stronger role on market discipline may lessen the moral hazard problem. But for market discipline to work effectively, depositors should have accurate information about the soundness of banks. This paper shows that in the absence of accurate information, information external-

ities and herd behavior of depositors can lead to runs on healthy banks. This undermines the role of market discipline in keeping an eye on bank activities. Therefore disclosure of information on banks' structure, performance and risk positions should be enforced¹³. This is "pillar three" of Basel II regime and this should be fully pursued to increase the effectiveness of market discipline, which can be an alternative for deposit insurance in achieving financial stability.

We can summarize the two main results of this paper as:

- In the presence of noisy private signals, for a significant set of parameter values, the optimal deposit contract allows for bank runs even if they can be generated by herd behavior of depositors and they can be on healthy banks.
- In the absence of perfect information on bank's performance, a deposit contract, with liquidity support from the central bank, cannot achieve the first-best efficient outcome.

The rest of the paper is organized as follows. The model is described in Section 2. In Section 3, I present the special case where the bank's return

¹³Rochet and Vives (2002) finds different results on the optimal disclosure policy of the Central Bank. They use the "global games" analysis of Carlsson and van Damme (1983) and find a unique equilibrium. In this unique equilibrium, there is an intermediate range of fundamentals where there is a potential for a coordination failure. Central Bank, by providing information that becomes common knowledge, can move the interbank market into a regime of multiple equilibria when the fundamentals are in that intermediate range. By adding noise to its announcements, Central Bank prevents switching to the regime of multiple equilibria. But they have a simultaneous move game while my model is a sequential move model of bank runs.

is publicly observed that serves as a benchmark model. Section 4 describes the information structure of the model with private noisy signals. I investigate different deposit contracts the bank can choose in Section 5. Section 6 analyzes the effect of liquidity support from the central bank and investigates whether it can prevent runs on healthy banks. Section 7 elaborates on policy implications of the model, in particular on transparency and disclosure of information on bank's performance and management of the crisis. Concluding remarks are in Section 8.

1.2 The Model

The model is similar to the models of DD and AG. The main difference is that we have an infinite number of depositors rather than a continuum. This way, I can develop a model of bank runs, where depositors move sequentially, and therefore, incorporate information externalities into the model. As mentioned in Brunnermeier (2001), this is a more realistic representation of bank runs in the real world and will help me investigate the role of herding and information externalities as a source of bank runs.

There are three periods, $t = 0, 1, 2$ and a single consumption good available at each date.

There is a bank that offers depositors a deposit contract and makes in-

vestments on their behalf. I assume that the banking sector is competitive so that the bank chooses the deposit contract that maximizes the welfare of depositors.

There are two assets : a *safe* and a *risky asset*. The safe asset is a storage technology that pays one unit at date $t + 1$ for each unit invested at date t . Both the depositors and the bank have access to the safe asset.

The risky asset that pays a random return of $\tilde{R}$ at $t = 2$ for each unit invested at $t = 0$, where

$$\tilde{R} = \begin{cases} R & \text{with probability } 1/2 \\ r & \text{with probability } 1/2 \end{cases}.$$

We have $r < 1 < R$ so that the risky asset does not dominate the safe asset. Only banks have access to the risky asset. Risky asset can be liquidated at $t = 1$ but only with some discount. When liquidated early, only a fraction τ of the return can be collected. Therefore the return at $t = 1$ is $\tau\tilde{R}$ where $\tau \in (0, 1)$.

There is an infinite number of depositors. A depositor can be an *early* or a *late consumer*. Early consumers value consumption at $t = 1$ only, while late consumers value consumption at $t = 2$. I assume that the types are public

information when realized but the bank cannot write type specific contracts¹⁴. Ex-ante, depositors do not know their type but they know the probability distribution over types. Probability of being an early consumer is λ and since there is an infinite number of depositors, λ is also the proportion of early consumers. As a result, there is no aggregate uncertainty resulting from the proportion of depositors that are subject to the liquidity shock.

Therefore consumers have the following preferences :

$$U(c_1, c_2) = \begin{cases} u(c_1) & \text{with probability } \lambda \\ u(c_2) & \text{with probability } 1 - \lambda \end{cases}$$

where c_t denotes consumption at date $t = 1, 2$. u is strictly increasing ($u' > 0$) and strictly concave ($u'' < 0$). Further, it satisfies the Inada conditions: $u'(0) = -\infty$ and $u'(\infty) = 0$. Depositors have an initial endowment of 1 unit of the consumption good at $t = 0$ and nothing at $t = 1$ and $t = 2$.

1.3 Publicly Observed Return

In this section, I assume that the realization of $\tilde{R}$ is publicly observed at $t = 1$. Since $\tilde{R}$ can take only two values, the following is just a simplified version

¹⁴See Section 3.2 for a discussion.

of AG. For this special case, I will find the first-best efficient outcome and show that a deposit contract with liquidity support from the central bank can achieve the first-best efficient outcome.

1.3.1 First-Best Efficient Outcome

For the moment, I assume that the bank can write contracts conditional on $\tilde{R}$. Therefore, the resulting allocation will be the first-best allocation (for a detailed discussion see AG).

I assume that the risky asset cannot be liquidated at $t = 1$, for now.

The bank will choose a portfolio of the safe (L) and the risky asset (X) out of the initial endowment 1 at $t = 0$ and will also determine the consumption levels $c_t(\tilde{R})$ conditional on the realization of $\tilde{R}$ that maximize the ex-ante expected utility of the representative depositor. So the bank's problem can be written as:

$$(P1) \left\{ \begin{array}{ll} \max & E[\lambda u(c_1(\tilde{R}) + (1 - \lambda)u(c_2(\tilde{R})))] \\ s.t. & (i) \quad L + X \leq 1 \\ & (ii) \quad \lambda c_1(\tilde{R}) \leq L \\ & (iii) \quad \lambda c_1(\tilde{R}) + (1 - \lambda)c_2(\tilde{R}) \leq L + \tilde{R}X \\ & (iv) \quad c_1(\tilde{R}) \leq c_2(\tilde{R}) \end{array} \right.$$

The first constraint is the feasibility constraint for the portfolio chosen at $t = 0$. Since the risky asset cannot be liquidated, the second constraint insures that the bank has enough safe asset to pay early consumers. The third constraint insures that the consumption levels provided by the deposit contract can be achieved. The last constraint is an incentive compatibility constraint to separate early and late consumers.

Since $u(\cdot)$ is strictly concave, the FOC uniquely characterizes the optimum. Depositors are risk averse so the best arrangement when everyone cannot be paid $\frac{L}{\lambda}$ is to distribute all funds equally among all depositors. This gives us the payoffs explained in Table 1 where the optimal level of L and X are given by the first-order conditions¹⁵.

¹⁵See Allen and Gale (1998) for a detailed discussion.

1.3.2 Optimal Deposit Contract

Now I will look at whether a bank that uses a deposit contract can achieve the first-best efficient outcome.

Though the bank observes the types of depositors when realized, I assume that it cannot write type specific contracts or suspend payments according to types. In my model, suspension of payments amounts to default on the deposit contract¹⁶. The bank has to use the sequential service constraint except for some cases, as I will explain now¹⁷.

I assume that the bank uses the following payment rule: In making its payments, bank uses the first-come first-served rule. When there is a run, the bank abandons the first-come first-served rule. Rather, it pays everybody the promised if it can and if it cannot, it divides whatever it has equally among those who demand liquidation.

When the risky asset cannot be liquidated early, AG shows that the expected utility from the first-best efficient outcome can be achieved by a standard deposit contract that promises a fixed payment. Bank pays its promises using the liquid asset and if it does not have enough liquid asset to make the

¹⁶In a larger contract space, there can be other arrangements that achieve higher levels of depositor welfare. These types of arrangements are not feasible in my contract space.

¹⁷Though suspensions of payments occurred on some occasions in the nineteenth century in US, Commercial Bank Clearing House was responsible for deciding whether and when the suspension was appropriate. Marine National Bank was punished for suspending payments on its own in May 1884.

promised payment, it divides all the liquid asset equally among those who demand early liquidation.

Let $\bar{c}_1$ denote the fixed payment promised to the early consumers. First we simplify the bank's problem using the bank's payment rule, to get:

$$(P2) \begin{cases} \text{Max} & \frac{1}{2} u(c_1(r)) + \frac{1}{2} [\lambda u(\bar{c}_1) + (1 - \lambda) u(c_2(R))] \\ \text{s.t.} & (i) \quad L + X \leq 1 \end{cases}$$

If the bank chooses $\bar{c}_1 = L/\lambda$, the deposit contract can achieve the first-best efficient outcome given in Table 1.

Now we relax the assumption that the risky asset can be liquidated at $t = 1$. When liquidated at $t = 1$, the return is $\tau \tilde{R}$ where $\tau \in (0, 1)$.

The bank has to liquidate the risky asset if it cannot pay $\bar{c}_1$ to depositors who demand early liquidation.

Under the possibility of costly liquidation, the deposit contract cannot achieve the first-best outcome from Table 1, since the bank has to go under costly liquidation when $\tilde{R} = r$. But when the central bank provides liquidity, the bank does not have to go under costly liquidation. In that case, the deposit contract of (P2) is feasible and can provide the expected utility from the first best allocation.

The following is a numerical example of the above discussion.

Example 1 Assume that $u(x) = \ln(x)$ and $\lambda = 1/2$. The optimal deposit contract can provide the first-best efficient expected utility. For low fundamentals ($R = 4, r = 0.5$), $E(U) = 0.2269$, the optimal portfolio is $(L, X) = (0.6404, 0.3596)$ and $\bar{c}_1 = 1.2808$. For high fundamentals ($R = 6, r = 0.75$), $E(U) = 0.3861$, the optimal portfolio is $(L, X) = (0.5687, 0.4313)$ and $\bar{c}_1 = 1.1375$.

We saw that a deposit contract, with liquidity support from the central bank, can achieve the first-best efficient outcome when the return from the bank's investment is publicly observed. When the return is publicly observed, runs are correct runs. In other words, they occur only when they are needed to occur. But as Park (1991) empirically documents, in the absence of perfect information about the bank's asset quality, healthy banks have also experienced runs. In those cases, liquidity support did not prevent runs. The policies that prevented runs on sound banks revealed the asset quality of banks. In the following sections, consistent with the empirical evidence, I will show that liquidity support from the central bank cannot prevent runs on healthy banks in the absence of perfect information about the bank's assets. Under those conditions deposit contracts cannot achieve the first-best efficient outcome with public informatio

1.4 Noisy Private Signals

In this section, I will explain the information structure of the model with noisy private signals. The structure is similar to the discrete signals social learning model of Bikhchandani, Hirshleifer and Welch (1992) (BHW from now on). Depositors will receive noisy signals about the quality of the bank's portfolio, namely about the return of the risky asset. These signals are informative but not perfect. Therefore the signal of each depositor have value for other depositors.

Initially, there is an exogenous order for depositors to make their decisions. At $t = 1$, depositors learn their type and if they happen to be a late depositor, their private signal about the bank's asset quality¹⁸. Basically, depositors receive a vector of signals with two dimensions: (Type, Signal). These vectors can be: $(e, \emptyset)$, (l, s_g) , (l, s_b) where e stands for an early consumer, l stands for a late consumer, s_g stands for a *good signal* which predicts the high return R , while s_b stands for a *bad* signal which predicts the low return r .

As I assumed, the bank and the depositors can observe types¹⁹. The con-

¹⁸Early depositors can receive a signal about the bank's prospects, too. It would not effect my results.

¹⁹This assumption makes the analysis simple without sacrificing from the content of the model. Chari and Jagannathan (1988) builds a model where depositors are faced with a signal extraction problem. They see a queue in front of the bank but they cannot identify the exact reason, which can be a high realization of the liquidity shock or some bad news about the bank's performance.

sequences of relaxing this assumption are discussed in the Appendix A²⁰.

As explained, late depositors privately receive a noisy signal s about the likelihood of the high return. The signals of different depositors are assumed to be independent, conditional on the true return of the risky asset. Conditional probabilities for the signals, given the true state, are :

$$q = \Pr(s_g | \tilde{R} = R) = \Pr(s_b | \tilde{R} = r)$$

$$1 - q = \Pr(s_g | \tilde{R} = r) = \Pr(s_b | \tilde{R} = R).$$

Note that $q \in (1/2, 1)$ so that the signals are informative but not perfect. And as q increases, signals become more informative. Probabilities of signals in different states are summarized in Table 2.

1.4.1 Updating

Now I will show how depositors update their beliefs about the good state. I assume that they use Bayes' rule in updating their beliefs. Let $p_g(p)$ and $p_b(p)$ be the posterior probability of the good state attached by a depositor who

²⁰This will contribute noise to the model. Now a withdrawal decision will be noisy information about a bad signal. If a depositor decides to withdraw at $t = 1$ it can be for two reasons:

- i) She may be an early consumer.
- ii) She may be a late consumer and observed a bad signal.

observe the good and the bad signal respectively, starting with a prior of p . To save notation, I will use p_g and p_b instead of $p_g(1/2)$ and $p_b(1/2)$, respectively. Assuming that agents update their beliefs using Bayes' rule, we get:

$$p_g = \frac{(1/2)q}{(1/2)q + (1/2)(1-q)} = q.$$

In the same way, we get:

$$p_b = 1 - q.$$

I assume that depositors value signals equally. As a direct consequence of this, good news revealed by a good signal will be washed out by bad news from a bad signal. This result is formally stated below:

Claim 1 $\forall q \in (\frac{1}{2}, 1)$, $p_g(p_b(1/2)) = p_b(p_g(1/2)) = \frac{1}{2}$.

P roof. I will show that $p_g(p_b(1/2)) = 1/2$. The other case is similar. To find $p_g(p_b)$, I will substitute $p_b = (1 - q)$ for p in $p_g(\cdot)$ and get:

$$p_g(p_b) = \frac{(1-q)q}{(1-q)q + q(1-q)} = \frac{1}{2}.$$

■

Now we examine how depositors update their beliefs when they observe a history of signals.

I assume that the actions of depositors are observable. For the moment, suppose that the depositors can perfectly infer the signals of the other depositors from their actions. They will update their beliefs about the good state on the basis of their own private signal and the publicly observed actions of depositors who moved before them.

As I showed above, good news revealed by a good signal will be washed out by the bad news from a bad signal. For this reason, for depositor i , in updating her belief, the only thing that matters is the difference between the number of good signals (n_g^i) and the number of bad signals (n_b^i) revealed by the actions of depositors who moved before her, $(a^1, \dots, a^{i-1})$, and her private signal (s^i). Therefore, all the information in $(a^1, \dots, a^{i-1}, s^i)$ can be summarized as the difference of the number of good and bad signals. Formally speaking, $n^i = n_g^i - n_b^i$ is a sufficient statistic.

Note that the history is carried through the public belief about the good state. I will call the public belief of the high return, when it is player i 's turn to move, as p^i , which is going to be the state variable.

I would like to explain the order in which depositors move, in more detail. This part of the analysis has differences from BHW and there will be an

endogenous component in depositor's timing²¹.

Initially, there is an exogenous order for players' decisions. Yet, while a withdrawal decision is irreversible, a non-withdrawal decision is not. A depositor who chose not to withdraw when it was her turn to move, is still in the game and can decide to withdraw later when it is her turn to move again²². In that sense the decisions are about the timing of withdrawals, which adds an endogenous component to the model. Figure 3 summarizes the sequence of events in this model.

1.5 Contracts with Noisy Private Information

In this section, I will investigate different deposit contracts the bank can choose. These contracts will have different probabilities of bank runs.

The first contract I will analyze, completely eliminates runs. I will call this the *run-proof contract*. Since runs carry early liquidation costs, this can be a desirable property of a deposit contract. But to be able to prevent runs, the bank will have to promise a small amount to early withdrawing depositors so that even a late depositor who observed the bad signal will get a higher expected payoff by not withdrawing at $t = 1$. Therefore the run-proof contract

²¹We do not have many social learning models where players' timing is endogenous. An excellent exception is Gale and Chamley (1994).

²²For simplicity I assume that she goes to the back of the line.

sacrifices from the insurance it provides against liquidity shocks.

Also, when we look at the first-best efficient outcome with public information, we see that when the bank cannot pay everybody the promised amount, the best arrangement is to distribute all the available funds equally among all depositors. But when bank runs are eliminated, early depositors will get their promised amount and if the return from the bank's investments is low, late depositors will get very little. This is another cost of eliminating runs completely. For these reasons, it is clear that the run-proof contract cannot achieve the first-best efficient outcome. Furthermore, it may be optimal to allow for bank runs.

Another contract, the bank can choose, is one that allows for runs. I will call this the *run contract*. This contract can provide higher levels of insurance against liquidity shocks since it is not bounded by the restrictions of the run-proof contract. But, because of the information structure of the model, withdrawal decisions can reveal information about the private signals of depositors. These signals possess valuable information for other depositors. As I will show, these information externalities can trigger a run on a sound bank.

When we compare the run contract with the first-best efficient outcome, we see that another shortcoming of this contract is that late depositors may choose to wait when they should run, as a result of information externalities.

Though the run contract can perform better than the run-proof contract, for the explained reasons, it cannot achieve the first-best efficient outcome.

In this section I will formalize the deposit contracts discussed above.

1.5.1 Run-Proof Deposit Contract

In this section, I will analyze the deposit contract that completely eliminates runs. For this contract to work, the bank should promise a small enough return to the early withdrawing depositors, so that even a late consumer with the bad signal will prefer to wait until the last period.

When this deposit contract is used, no late depositor will withdraw early and the actions of late depositors will be independent of their private signals. No new information will be revealed during the course of the game. This creates an informational cascade as defined below.

Definition 1 *In an informational cascade, depositors choose the same action, regardless of their private signals²³.*

Since no new information is revealed, the public belief p^i will always be equal to the prior belief of $1/2$, for all depositors. All late depositors will be in the same situation as the first depositor and they will decide to wait until the

²³*In this discrete signals setup, herds and cascades are equivalent. For a distinction between the two, see Smith and Sorensen (2000).*

last period. We will be in an informational cascade where no late depositor withdraws early. I will call this a *no-run cascade*.

There is another informational cascade in which late depositors choose to withdraw early regardless of their private signals. I will call this a *run-cascade*.

The run-proof contract can increase the welfare of depositors since runs carry early liquidation costs. But the liquidity insurance provided by these deposit contracts can be very low since the bank has to promise a small amount to early withdrawing depositors. And also, when the return from the risky asset is low, the optimal arrangement is to distribute the whole portfolio equally among all depositors, but the run-proof contract cannot achieve this.

Late depositors do not run with this type of contract and early depositors get the promised amount $\bar{c}_1$ in both states through the liquid asset. Since λ of the depositors will turn out to be early depositors, bank will invest λ of the funds in the safe asset. Late depositors, who will be $(1 - \lambda)$ of the population, will get the funds invested in the risky asset at the end. Therefore, late depositors will get:

$$c_2(\tilde{R}) = \begin{cases} \frac{(L - \lambda \bar{c}_1) + R X}{1 - \lambda} & \text{if } \tilde{R} = R \\ \frac{(L - \lambda \bar{c}_1) + r X}{1 - \lambda} & \text{if } \tilde{R} = r. \end{cases} \quad (1.1)$$

Now, let's look at the constraints needed for the run-proof contract to work.

The first late depositor, upon observing the bad signal, should wait until the last period. If she withdraws, she gets $\bar{c}_1$. Now her posterior about the good state is $p_b = 1 - q$ and if she does not withdraw, she will get an expected utility of $[(1 - q) u(c_2(R)) + q u(c_2(r))]$. If the bank offers $\bar{c}_1$ such that

$$u(\bar{c}_1) \leq (1 - q) u(c_2(R)) + q u(c_2(r)), \quad (1.2)$$

the first depositor, upon observing the bad signal, will not withdraw. The first depositor's decision did not reveal any information about her private signal. When it is the second late depositor's turn to move, the public belief about the good state is still $1/2$. She is in the same situation as the first late depositor and because of inequality (2) she will not withdraw either. The analysis will continue in this fashion and no late depositor will withdraw early.

Under this contract, early depositors get $\bar{c}_1$ while the late depositors get $c_2(\tilde{R})$.

We can write the bank's problem as:

$$(P3) \left\{ \begin{array}{ll} \text{Max} & \lambda u(\bar{c}_1) + (1 - \lambda) \left[\frac{1}{2} u(c_2(R)) + \frac{1}{2} u(c_2(r)) \right] \\ \text{s.t.} & (i) \quad L + X \leq 1 \\ & (ii) \quad u(\bar{c}_1) \leq (1 - q) u(c_2(R)) + q u(c_2(r)) \end{array} \right.$$

where $c_2(R)$ and $c_2(r)$ are the same as in (1).

This contract will completely eliminate bank runs. Given that early liquidation is costly, preventing runs can increase welfare. But, note that the constraint (ii) becomes more binding as the informativeness of the private signals, q , increases. As q increases, the right-hand side of (ii) decreases. Therefore to satisfy this constraint, the bank has to offer a smaller amount to early depositors. This will undermine the insurance provided by the deposit contract against a liquidity shock. It is clear that the run-proof contract cannot achieve the first-best efficient outcome.

Also note that the constraint (ii) depends on the fundamentals. If the fundamentals are sound, formally high R and/or high r , then (ii) can be satisfied for a wider range of $\bar{c}_1$ values. Therefore when the fundamentals are not strong, preventing runs will have higher costs.

As $\bar{c}_1$ increases the left-hand side of (ii) increases while the right-hand side decreases. Therefore depending on the parameters of the model (q, R, r), there

is a critical level of $\bar{c}_1$, denoted by $\underline{c}$, such that when $\bar{c}_1$ is above $\underline{c}$, (ii) is not satisfied. Note that $\underline{c}$ is decreasing in q , increasing in R and r (see Figure 1).

In the following example, I illustrate these ideas.

Example 2 Assume that $u(x) = \ln(x)$ and $\lambda = 1/2$. At $\bar{c}_1 = \underline{c}$, the left-hand side is equal to right-hand side in constraint (ii). We get

$$\ln(\underline{c}) - \ln(2 - \underline{c}) = (1 - q) \ln(R) + q \ln(r).$$

When we take the exponential of both sides, we get

$$\frac{\underline{c}}{2 - \underline{c}} = R^{(1-q)} r^q.$$

So that

$$\underline{c} = \frac{2R^{(1-q)} r^q}{1 + R^{(1-q)} r^q}.$$

Note that $\frac{\partial \underline{c}}{\partial q} < 0$, $\frac{\partial \underline{c}}{\partial R} > 0$, $\frac{\partial \underline{c}}{\partial r} > 0$. Figure 1 presents the relationship between $\underline{c}$ and q (dashed lines) for high ($R = 6, r = 0.75$) and low fundamentals ($R = 4, r = 0.5$). And Figure 2 shows the expected utility provided by the run-proof contract (dashed lines), as a function of q , for high ($R = 6, r = 0.75$) and low fundamentals ($R = 4, r = 0.5$).

1.5.2 Deposit Contract with Bank Runs

In this section, I will analyze the deposit contract that allows for bank runs. This contract will not have the restrictions of the run-proof contract, therefore it can provide higher levels of insurance against liquidity shocks. Yet information externalities and herd behavior of depositors can trigger runs on healthy banks. This will be the counterfeit of the liquidity insurance provided by this contract.

I assume that actions of depositors are observable. The deposit contract I will analyze will have the following features²⁴:

- A depositor with the posterior of $p_b = 1 - q$, will withdraw early.
- A depositor with the posterior of $1/2$, will not withdraw early.
- A depositor with the posterior of $p_g = q$, will not withdraw early.

If it is better to wait with a posterior of $1/2$, it should also be better to wait when the posterior is q . Therefore the third property will be automatically satisfied when the second one is satisfied.

In this deposit contract, whenever the public belief about the good state reaches a level of q , from then on no late depositor will withdraw. When the public belief reaches a level of q , even a depositor with the bad signal will

²⁴These features hold for a depositor for whom an informational cascade has not started yet.

have a posterior of $1/2$ and because of the second property, this depositor, say depositor i , will decide to wait until the last period. Note that her action does not depend on her private signal, therefore no new information has been revealed. So the public belief when it is the $(i + 1)th$ depositor's turn to move is still q and she will be in the same position as the i th depositor. This starts a no-run cascade where no late depositor will withdraw early.

Also note that when the public belief drops to a level of $p(-2)^{25}$ even a depositor with the good signal will withdraw early, since her posterior, taking into account her private signal, will be equal to $(1 - q)$ and by the first property, she should withdraw. Her action will not reveal any new information. All the depositors after her will be in the same situation and they will also withdraw early. Therefore, whenever the public belief drops to a level of $p(-2)$, a run on the bank will be triggered.

Now I can calculate the probabilities of each type of cascade (run and no-run cascades) in different states of nature using the discussed features of the deposit contract. The analysis will be very similar to that in BHW: I will start with the first late depositor and go forward sequentially. Since I assume that the depositors can observe each other's type, in updating their beliefs, late depositors will not take into account the withdrawal decisions of early

²⁵This notation has been explained in section 2.2. It corresponds to a sequence of signals where the number of bad signals is two more than the number of good signals, $n^i = n_g^i - n_b^i = -2$.

depositors. Therefore, for the following discussion, I will concentrate on late depositors only.

I will start with the first late depositor. Her action, $a^1 \in \{W, N\}$ where W and N stand for withdraw and not-withdraw at $t = 1$ respectively, will depend on her private signal. If she had the good signal, she will not withdraw. Now the public belief is q and this starts a no-run cascade. If she had the bad signal, she would withdraw but a run-cascade will not start yet.

Let's look at the second late depositor. If the first late depositor did not withdraw, she is in a no-run cascade and will not withdraw, regardless of her signal. If the first late depositor withdrew early, then the public belief is $(1 - q)$. If she observed the good signal, her posterior is $1/2$, therefore she will not withdraw. If she observed the bad signal, her posterior is $p(-2)$ and she will withdraw. This will trigger a run on the bank.

The only history where a cascade has not started by the third late depositor is $(a^1, a^2) = (W, N)$. For that history, the public belief is $1/2$ and the third depositor is in the same position as the first late depositor. If she observed the good signal, she will not withdraw and this will start a no-run cascade. If she observed the bad signal, she will withdraw early.

A cascade has not started by the fourth late depositor only when the history is $(a^1, a^2, a^3) = (W, N, W)$. In that case, the fourth late depositor is in the same situation as the second late depositor. Otherwise she is in a cascade and her

action will not depend on her private signal.

The analysis continues in this manner.

Next I will calculate the probabilities for run and no-run cascades in both states. Note that the only sequence of actions where a cascade does not start has repetitions of (W, N) s, possibly followed by a W . Otherwise, a cascade starts.

Now, suppose it is the good state. Table 3 shows the probabilities of these cascades for the second and the n th late depositor.

The probability of a no-run cascade **until** the n th late depositor is :

$$P_n(no - run|G) = \sum_{j=0}^{(n/2)-1} q[(1-q)q]^j = q \left(\frac{1 - [(1-q)q]^{(n/2)}}{1 - (1-q)q} \right)$$

When we look at the asymptotic properties of this probability, we get:

$$\lim_{n \rightarrow \infty} P_n(no - run|G) = \frac{q}{1 - q(1 - q)} = P(no - run|G).$$

Other probabilities can be calculated using the same analysis. Probabilities for run and no-run cascades in each state are given in Table 4.

Using these probabilities, I will formally write the run contract.

Now, I will write the constraints of the run contract. These constraints are valid for a depositor for whom a cascade has not started yet. The bank

uses the payment rule explained in section 3.2. When a run starts, the bank will not use the first-come first-served rule but cumulate withdrawals²⁶. The constraints for those cases will be discussed later.

The first property of this contract is that a depositor with a posterior of $(1 - q)^{27}$ will prefer to withdraw. If she withdraws early, she guarantees herself $\bar{c}_1$. If she deviates and waits, others will think she observed the good signal. This will start a no-run cascade and no other late depositor will withdraw early. Note that this is the highest outcome a depositor can get from waiting, since liquidation of the risky asset is costly. To satisfy this, we need

$$u(\bar{c}_1) > q u(c_2(r)) + (1 - q) u(c_2(R)). \quad (1.3)$$

According to the second property of this contract, a depositor with a posterior of $1/2^{28}$ should wait. The consequences of this constraint is not as immediate as the previous one since this action will not start an informational cascade. The return from waiting will be random depending on the state as in other cases, but also on what the depositors after her will do.

²⁶Wallace (1988) and Wallace (1990) argue that the sequential service constraint is not the optimal arrangement under some conditions.

²⁷The only case where a cascade has not started by this depositor is that the decisions before her were repetitions of (W, N) s and she observed the bad signal s_b .

²⁸The only case where a cascade has not started by this depositor is that the decisions before her were repetitions of (W, N) s followed by a W , and she observed the good signal s_g .

We can have run and no-run cascades in both the good and the bad state. A player's payoff depends on the state as well as the occurrence of a run as summarized in Table 5.

If there is no run on the bank then late depositors get the return from the risky asset which is the same as in the run-proof contract, given in (1):

$$c_2(\tilde{R}) = \begin{cases} \frac{(L-\lambda\bar{c}_1)+RX}{1-\lambda} & \text{if } \tilde{R} = R \\ \frac{(L-\lambda\bar{c}_1)+rX}{1-\lambda} & \text{if } \tilde{R} = r. \end{cases}$$

If a bank run starts at some point, the late depositor who chose not to withdraw when it was her turn can join the run. But now she cannot guarantee herself $\bar{c}_1$ since the bank cumulates withdrawals and pays everyone $\bar{c}_1$ if it can, but if it cannot, it equally divides whatever is available among those who demand early liquidation. If $\tau > \bar{c}_1/R$, even the risky asset is liquidated at a discount, everybody can get their promised of $\bar{c}_1$ in the good state. In the bad state and in the good state when $\tau < \bar{c}_1/R$, the bank cannot pay everybody the promised so it equally divides whatever it has among those who wants to withdraw.

Using these payoffs from Table 5 and the probabilities from Table 4, we get the constraint for a late depositor with a posterior of 1/2 not to withdraw, as:

$$\begin{aligned}
u(\bar{c}_1) &< \frac{1}{2(1-q(1-q))} \left[\begin{array}{l} q u(c_2(R)) + (1-q) u(c_2(r)) + \\ (1-q)^2 u(c_1^{Run}(R)) + q^2 u(c_1^{Run}(r)) \end{array} \right] \\
&= E(U^{late})
\end{aligned}$$

When a run is triggered, the late depositors who chose not to withdraw when it was their turn to move can choose to join the run. This adds an endogenous component to the timing of withdrawal choices. We may need different constraints for them to choose to join²⁹.

²⁹A run is triggered when the public belief drops to $p(-2)$. The bank no longer uses the first-come first-served rule. Payoffs from not withdrawing when it is her turn to move but joining the run later are different from the payoffs in Table 5. If a late depositor joins the run and if it is the good state, she gets $\bar{c}_1$ when $\tau > \bar{c}_1/R$, she gets $L + \tau R X$ when $\tau < \bar{c}_1/R$. If she joins the run and if it is the bad state, she gets $L + \tau r X$. If she does not join the run, she gets $c_2^{Run}(\tilde{R})$ which is $c_2(R)$ if it is the good state and $\tau > \bar{c}_1/R$, and 0 otherwise. That is:

$$c_2^{Run}(R) = \begin{cases} c_2(R) & \text{if } \bar{c}_1 \leq \tau R \\ 0 & \text{if } \bar{c}_1 > \tau R \end{cases}$$

and $c_2^{Run}(r) = 0$.

For her to join the run we should have

$$(1-q) u(c_1^{Run}(R)) + q u(c_1^{Run}(r)) > (1-q) u(c_2^{Run}(R)) + q u(0).$$

Assuming that $u(0)$ is a small enough number, we can satisfy this constraint easily (for example $u(.) = \ln(.)$).

Now we can state the bank's problem:

$$(P4) \left\{ \begin{array}{ll} \text{Max} & E(U^{early}) + E(U^{late}) \\ \text{s.t.} & (i) \quad L + X \leq 1 \\ & (ii) \quad u(\bar{c}_1) > q u(c_2(r)) + (1 - q) u(c_2(R)) \\ & (iii) \quad u(\bar{c}_1) < E(U^{late}) \end{array} \right.$$

where $c_2(R)$, $c_2(r)$, $c_1^{Run}(R)$ and $c_1^{Run}(r)$ are the same as in Table 5³⁰.

Now I would like to investigate how the parameters of the model (q, R, r, τ) will affect the constraints and the objective function.

First we observe that the critical value of $\bar{c}_1$ for constraint (ii) to be satisfied is $\underline{c}$, the critical value for the constraint in the run-proof contract. This constraint is satisfied for values of $\bar{c}_1 > \underline{c}$. We have seen before that $\underline{c}$ decreases in q and increases in R and r . Therefore keeping other parameters constant, as the informativeness of the signals increase, this constraint becomes less binding, which increases the welfare provided by the run-contract.

The LHS of (iii) is increasing while the RHS is decreasing in $\bar{c}_1$. Therefore

³⁰In this type of contract, if there is no run, all early depositors get the promised $\bar{c}_1$. If there is a run, they get $c_1^{Run}(R)$ in the good state and $c_1^{Run}(r)$ in the bad state. Ex-ante, the probability of the good state is 1/2 and using the probabilities from Table 4, we find the expected utility of the early depositors as:

$$E(U^{early}) = \frac{1}{2(1 - q(1 - q))} [u(\bar{c}_1) + (1 - q)^2 u(c_1^{Run}(R)) + q^2 u(c_1^{Run}(r))].$$

there is a critical level of $\bar{c}_1$, denoted as $\bar{c}$, above which (iii) is not satisfied.

It is not clear whether the RHS of (iii) will increase or decrease as the signals become more informative. Therefore the effect of more informative signals is ambiguous on this constraint.

Now I would like to investigate how fundamentals (R, r) affect the constraint and the objective function. As R and r increases, RHS of (ii) increases so we need higher values of $\bar{c}_1$ to satisfy this constraint. It makes this constraint more binding. But this increases the RHS of (iii) and makes it less binding. So when the fundamentals are strong, it is not clear whether the choice set becomes larger or smaller. Clearly, strong fundamentals have a positive effect on the objective function.

As the liquidation cost goes down, constraint (ii) is not affected, while the RHS of constraint (iii) increases so that the bank's choice set becomes larger. This is because when the liquidation costs are low, the cost of bank runs is low. Note that as τ increases, the objective function also increases. Therefore a low liquidation cost makes the run contract more attractive.

Though the run contract can give better results than the run-proof contract, it is quite clear that it cannot achieve the first-best efficient outcome. In the next section I will investigate how the liquidity support can improve the run contract but even in that case, it cannot achieve the first-best efficient outcome.

1.6 Liquidity Support

In this section I will introduce a central bank that will act as a *lender of last resort* and provide liquidity support to the bank. This liquidity support will improve the run contract since the bank does not have to go under costly liquidation of the risky asset when faced with a run. But as I will show, in the absence of public information about the bank's soundness, liquidity support will not be enough to achieve the first-best efficient outcome with public information.

Bagehot (1873) recommends that in a time of crisis, a central bank should lend freely at a very high rate of interest and these loans should be made on all good banking securities. In my model, the central bank will lend only against good collateral³¹ as Bagehot (1873) recommends. Actually the best justification for this comes from Bagehot's own words: "Any aid to a present bad bank is the surest mode of preventing the establishment of a good bank³²".

However, I will not use the second rule which recommends to lend at a

³¹I assume that the central bank knows the value of the bank's assets when providing liquidity. For a discussion, see Section 7.

³²In practice, we see interventions when the bank is insolvent (Prati and Schinasi (1999) and Giannini (1999)). The justification for this is the possibility of contagion to the banking system (Diamond and Rajan (2002)). Since I have only one bank in my model, it is not a suitable model to study contagion. Another reason for interventions to insolvent banks is pointed out by Santomero and Hoffman (1998). They show that for US, between 1985 and 1991, access to the discount window was granted to banks that later failed. They argue that the reason for this was to keep institutions afloat so that the deposit insurance fund did not suffer further losses. This can be another destabilizing effect of deposit insurance.

very high rate. The central bank will lend at a zero interest rate in this model. Actually lending at a high rate can worsen the banking crisis³³ and can give managers the incentive to take very high, uneconomical risks. In practice, there have been episodes where Bagehot's rule of lending at a very high rate has been challenged, as Goodhart and Shoenmaker (1995) and Prati and Schinasi (1999) document.

With the liquidity support from the central bank, the bank does not have to go under costly liquidation of the risky asset. Simply it can lend the risky asset in its portfolio to the central bank which will provide liquidity at $t = 1$ in the amount that is equal to the value of the risky asset at $t = 2$. This contract is a special case of the run contract, $\tau = 1$ now.

The probabilities for run and no-run cascades in each state will be the same as in Table 4. The contract will be the same as the run contract in section 5.2. but the payoffs will come from Table 6 now.

³³See Garcia and Plautz (1988).

Now we can state the run contract. The bank's problem is:

$$P(5) \left\{ \begin{array}{ll} \text{Max} & E(U^{early}) + E(U^{late}) \\ \text{s.t.} & (i) \quad L + X \leq 1 \\ & (ii) \quad u(\bar{c}_1) > q u(c_2(r)) + (1 - q) u(c_2(R)) \\ & (iii) \quad u(\bar{c}_1) < E(U^{late}) \end{array} \right.$$

where $c_2(R)$, $c_2(r)$, $c_1^{Run}(R)$ and $c_1^{Run}(r)$ are the same as in Table 6.

Since this is a special case of the run contract, the parameters of the model (q, R, r) will affect the constraints and the objective function in the same way as before.

The following example focuses on constraint (iii) .

Example 3 Suppose $u(x) = \ln(x)$ and $\lambda = 1/2$. I would like to find the critical value $\bar{c}$. From constraint (ii) we get

$$(1 + q)^2 \ln(\bar{c}) - \ln(2 - \bar{c}) - q^2 \ln\left(\frac{\bar{c} + (2 - \bar{c})r}{2}\right) = q \ln(R) + (1 - q) \ln(r).$$

Taking the exponential of both sides, we get

$$\frac{\bar{c}^{(1+q)^2}}{(2 - \bar{c}) \left(\frac{\bar{c} + (2 - \bar{c})r}{2} \right)^{q^2}} = R^q r^{(1-q)}.$$

We can find the value of $\bar{c}$ below which (iii) is satisfied using the above equality.

Figure 1 (solid lines) shows the values of $\bar{c}$ for low ($R = 4, r = 0.5$) and high fundamentals ($R = 6, r = 0.75$).

Because of the explained trade-off of preventing runs, for some parameter values, it may be optimal to allow for runs even if they can be generated by herd behavior of depositors and can be on healthy banks. The relation between the parameters and the utilities provided by the contracts were explained within the text when we analyze how the parameters affect the constraints and the objective functions for each contract. The example below illustrates these points.

Example 4 *The table below shows the expected utilities from different contracts the bank can choose for different values of q with low fundamentals*

$(R = 4, r = 0.5)$

	<i>Run Contract with Liquidity</i>	<i>Run-Proof Contract</i>
$q = 0.60$	0.1319	0.1733
$q = 0.75$	0.1836	0.1695
$q = 0.90$	0.2147	0.1441

Figure 2 shows the expected utilities from run (solid lines) and run-proof (dashed lines) contracts with low ($R = 4, r = 0.5$) and high fundamentals ($R = 6, r = 0.75$). For low values of q , the run-proof contract is better but as q increases, allowing for runs becomes optimal. From Figure 2, we see that, for low fundamentals, the range of q values for which the run contract performs better than the run-proof contract is larger than the same range with high fundamentals. This is because, preventing runs have higher welfare costs when fundamentals are not strong.

Since the bank does not have to go under costly liquidation of the risky asset it is quite clear that the liquidity support improves the performance of the run contract. But as we saw, the liquidity support does not prevent runs on healthy banks, which is consistent with the historical evidence provided by Park (1991). For the run contract to achieve the first-best efficient outcome, it

is crucial that runs are correct, that is, they occur only when they are needed to. For these reasons, in the absence of perfect information about banks' asset quality, a deposit contract, even with liquidity support from the central bank, cannot achieve the first-best efficient outcome with public information.

1.7 Policy Implications

This paper makes important suggestions on the policy side. In my model, deposit insurance can prevent runs and since early liquidation is costly, this can be welfare improving. Yet it is a well-known fact that with deposit insurance³⁴, depositors do not have any incentive to differentiate between sound and unsound banks. In such an environment, weak banks do not have any difficulty in attracting deposits. This creates an opportunity for moral hazard on banks' side. Actually, some studies argue that guarantees create distortions and make bank failures more likely. Demirguc-Kunt and Detragiache (2000) analyze panel data for 61 countries during 1980-97 and concludes: "Explicit deposit insurance tends to be detrimental to bank stability, the more so when institutional environment is weak, when the coverage is extensive and when the insurance is run by the government³⁵."

³⁴For an excellent survey on deposit insurance practices and current discussions, see Garcia (2000).

³⁵In parallel with this finding, Schotter and Yorulmazer (2003) show that partial deposit insurance can diminish the severity of bank runs, therefore full deposit insurance can be

Financial regulators and policy makers have been looking for alternatives for full deposit insurance. Giving a greater role on market discipline may lessen the moral hazard created by guarantees. For market discipline to work effectively, depositors should have accurate information about the soundness of banks. As this paper shows, in the absence of accurate information, information externalities and herd behavior of depositors can trigger runs on healthy banks. This in turn undermines the role of market discipline in keeping an eye on bank activities. Therefore disclosure of information on banks' structure, performance and risk positions should be enforced. This is pillar three of Basel II regime and this should be fully pursued to increase the effectiveness of market discipline, which can be an alternative for deposit insurance in achieving financial stability.

Another important point with the disclosure of information is the continuous review of banks' performance which is "pillar two" of Basel II regime. In my model, I assume that the central bank knows the value of the bank's assets when providing liquidity. In some situations, it can be difficult for a central bank to identify the exact source of a problem in a bank, i.e. whether it is a solvency or a liquidity problem³⁶. Actually, Berger et.al (1998) test the

inefficient.

³⁶Diamond and Rajan (2001) build a model where liquidity and solvency problems interact. They show that bank failures can themselves cause liquidity shortages which may cause a total meltdown of the system.

hypothesis that supervisors have more accurate information than the market on the soundness of financial institutions for the US case. They show that shortly after supervisors have inspected a bank, supervisory assessment of the bank is more accurate than the market. But, for periods where the supervisory information is not up-to-date, market has more accurate information than the supervisors. By continuously (or frequently) reviewing bank's performance, authorities can take preemptive action and act rapidly when faced with banking problems. This can minimize the costs generated by disruptions to the payments system. In that sense, pursuing pillar two of the Basel II regime is crucial.

1.8 Conclusion

In this paper, I built a dynamic model of bank runs that allowed me to study important phenomena such as the role of information externalities and herd behavior of depositors as a source of bank runs. I showed that, in the presence of noisy private information, information externalities and herd behavior of depositors can trigger runs on healthy banks. The bank can choose a deposit contract that completely eliminates runs but this has some costs. That type of contract sacrifices from the insurance provided against liquidity shocks. Furthermore, in cases where the bank cannot pay everybody the promised amount,

it may be socially optimal to have a run, as shown in AG. These are some costs of completely eliminating runs.

The bank can also choose a deposit contract that allows for runs. For some parameter values, it can be optimal to allow for runs even they can be generated by herd behavior of depositors and they can be on healthy banks.

The results of the paper are in parallel with the empirical evidence on measures that prevent bank runs. While liquidity support alleviates the costs of early liquidation, it cannot prevent runs on healthy banks. The policy measure that will prevent wrong runs is the disclosure of information on banks' soundness and management of the crisis. A deposit contract, with liquidity support from the central bank, can achieve the first-best efficient outcome only in the presence of perfect information about the bank's performance.

Chapter 2

On the Severity of Bank Runs: An Experimental Study

Joint with Andrew Schotter

2.1 Introduction

For those of us living in the United States, there seems to be a perception that things like bank runs and other types of financial crises are no longer a matter of concern. The reality is that bank runs are still a constant feature of economies throughout the world. Lindgren, Garcia and Saal (1996) show that during the period 1980-96, of the 181 IMF member countries, 133 have experienced significant banking problems. Such problems have affected developed, as well as developing and transitional countries. For example, over the past 25 years banking crises have hit such developed countries as Finland (1991-93), Norway (1988-92), Japan (1992-present), Spain (1977-85), and Sweden (1991) and have recently troubled such developing countries as Russia (1998), Brazil (1999), Turkey (2000) and (2001) and Argentina (2001), and various countries in Asia (1997-98). These banking problems also have significant costs as many authors have documented (see, Lindgren, Garcia and Saal (1996), Caprio and Klingebiel (1996), Lindgren et.al. (1999), Alexander et.al. (1997), Sundararajan and Baliño (1991), Hoggarth, Reis and Saporta (2001)).

When one looks at the economic literature on bank runs (Diamond and Dybvig (1983), Allen and Gale (1998), Calomiris and Kahn (1991), Chari and Jagannathan (1988) and others) one sees a wide variety of models most of which have the same two features. With some variations, most of the models

on bank runs are static two-period equilibrium based models with a continuum of agents played in the normal or simultaneous move form. In many of these models, the bank run problem is viewed as an equilibrium selection problem embedded in a coordination game in which all agents would be better off if they did not create a run on the bank (remove their money early) while it is an equilibrium to both remove early and to remove late. In addition, they mainly focus on whether deposit contracts are optimal arrangements in the presence of the possibility of a bank run and try to find the Central Bank policy and other institutional arrangements to prevent runs or minimize the cost associated with them.

But Brunnermeier (2001) makes an important observation about the bank run models in the economic literature: "Although withdrawals by deposit holders occur sequentially in reality, the literature typically models bank runs as a simultaneous move game". And, since most of these models are static, they do not attempt to explain the severity of bank runs. In these models, bank runs either occur or they do not. But as we know, some bank runs are more severe than others and most of the theoretical literature on bank runs appears to be silent about such questions.

We concentrate on the severity of bank runs measured by how fast money is removed from the banking system after a crisis has developed and ask questions like:

- Are bank runs more severe (i.e. does money get withdrawn from the system more quickly) when depositors observe the action of other depositors and can see when they withdrew their money and how much they received?
- Are runs more severe when some depositors have insider information?
- Is the severity of bank runs influenced by cyclical factors in the economy, i.e., should we expect them to be more severe if they occur when the economy is in a down-cycle?
- Can partial deposit insurance be as effective as the usual full insurance in mitigating the severity of bank runs?

Some of these questions cannot be answered with two-period static models. Though there are some experimental studies on similar issues such as network formation and contagion, an excellent one being Corbae and Duffy (2002), micro data on most of these issues do not exist. Therefore we chose to examine these issues in the context of experiments using a dynamic model.

In this paper we look at the dynamics of bank runs and try to sort out what influences their occurrence and what interventions work in slowing them down. We basically look at two types of interventions - informational and insurance. With respect to the first we are interested in knowing whether there is certain

information, which, if released during the progress of a bank run, could slow it down. Such information, for example may be information about whether those who have removed their money from the bank were paid or not.

The insurance question we ask is how little insurance is needed to stop bank runs. The idea here is that full insurance may not be needed to stop bank runs and is not even desirable since in the presence of full insurance, depositors do not have any incentive to differentiate between sound and unsound banks. Weak banks do not have any difficulty in attracting deposits. This creates an opportunity for moral hazard on banks' side¹. Garcia (2000) recommends providing low coverage as a good practice but suggests that we also need to answer such questions as which deposits should be covered and at what level. In that context, our study is an attempt to discover which level of coverage is optimal. Hence, we test whether partial deposit insurance can prevent runs.

Finally, we investigate the role of asymmetric information in our bank run model. Here some set of agents or subjects are "insiders" who are informed of the state of the world (how sound their bank is) while others are not. We ask whether the presence of such insiders exacerbates or dampens the severity of bank runs during a crisis.

¹Some argue that guarantees create distortions and make bank failures more likely. Demirguc-Kunt and Detragiache (2000) analyzes panel data for 61 countries during 1980-97 and concludes that "explicit deposit insurance tends to be detrimental to bank stability, the more so when institutional environment is weak, when the coverage is extensive and when the insurance is run by the government".

We embed our experiment in a four period bank run model whose equilibria we calculate. The fact that we have four periods, instead of the usual two, allows us to investigate the dynamics of bank runs more easily than a two period model would.

Our experiments turn up a number of interesting findings that inform both theory and policy. First we find that bank-run behavior is influenced by the information that subjects have on hand when a crisis occurs. For example, in one treatment we run the experiment using a simultaneous play version or the normal form where all subjects choose when to withdraw their money from a bank at once and in ignorance of what the other subjects are doing. In another treatment they play the game in the extensive form where over a four-period horizon they decide period by period if they want to remove their money conditional on what has happened before them, i.e., how many people removed their money and what their payoffs were. We find that behavior is consistent with the predictions of the theory mostly when the game is played in the extensive form with high amounts of information given between periods (information describing how many people removed their money, what payoff they received etc.). This is despite the fact that behavior should be invariant to the game form. Since in the real world, bank runs are more typically played in the extensive form, this finding lends support to using theory as a guide to

behavior².

Second, we find that it is possible to delay or slow down bank runs by issuing minimal deposit insurance. More precisely, in some of our experiments we insure depositors by issuing insurance, which covers either 20% or 50% of what is owed them. We find that even with this minimal coverage, the withdrawal timing is significantly delayed. This is important, of course, since issuing full deposit insurance by the government (up to \$100,000) is both costly and creates adverse incentives for depositors, that is, depositors fail to engage in diligence when selecting a bank. On the other hand, partial insurance creates an incentive for consumers to monitor their banks.

Third, we show both theoretically and empirically that the presence of insiders actually increases welfare by leading subjects to remove their money later rather than sooner. Hence, *ceteris paribus*, money stays in the banking system longer when there is private insider information and that is a benefit in our model.

Finally, we also present evidence that the severity of a bank run depends on the state of the economy when a crisis occurs. More precisely, say that a consumer wakes up one morning picks up a newspaper and reads that there is a possibility of a banking crisis. If this news arrives when the economy is doing

²See Brunnermeier (2001). Some exceptions would be Chen (1999), Green and Lin (2003) and Yorulmazer (2003).

relatively well, i.e. when the mean rate of return in the banking industry is relatively high, then we would expect (and we find) that the severity of the banking crisis is less than when this news arrives during a downturn.

In this paper we will proceed as follows: In Section 2 we present the bank run model that underlies our experiment. In Section 3 we describe our experimental design and procedures. In Section 4 we describe theoretical results while in Section 5 we present our empirical findings. In Section 6 we describe our learning results and we present some conclusions and speculations in Section 7.

2.2 A Bank Crisis Model

Consider a community of six people all of whom deposit their money in the same bank. While this bank may have served them well in the past, they have no idea how the bank invests its money and hence they are never sure whether it can meet its obligations if called on to do so. To make this uncertainty more transparent assume that there are five types of banks in the economy, B_1 , B_2 , B_3 , B_4 and B_5 . We are calling Bank B_3 the mean bank B_m since it has a rate of return on its money that is the mean return in the five-bank banking industry. The other banks, B_1 , B_2 , B_4 and B_5 , are banks whose rate of returns are $1/3B_m$, $2/3B_m$, $4/3B_m$, $5/3B_m$ respectively. What this means

is that if the community's money is in the worse type of bank that bank earns a rate of return on its money equal to $1/3B_m$ or $1/3$ of the mean rate of return in the banking industry. Banks 4 and 5 are the better than average banks, those who have invested well. The bank that the community's money is in is drawn randomly with a uniform density $f_b = 1/5$, $b = 1, 2, 3, 4, 5$, so that the probability that any given bank is the relevant one is $1/5$.

Assume that time is divided into 4 discrete periods 1, 2, 3 and 4 and, that all money must be withdrawn at the end of the fourth period if it is kept there that long. This is a stylized version of a bank crisis since it requires that agents think of when they should withdraw their money knowing that the other agents are thinking about the same thing. The need to think about removing your money may have been caused by an external event, which is left un-modeled here (a newspaper headline that a major bank has failed elsewhere or major embezzlements discovered by the press). So this is a model of an existing bank crisis since the question is not whether an agent should remove his money from the bank but, rather, when.

The bank promises to pay a promised rate of return on the money deposited in it of r' and will do so if it has the funds to pay when people request them. If it does not, then it will pay each person who wants to withdraw, an equal share of what it has on hand.

Each person starts off with $\$K$ to deposit and if it keeps its money in the

bank for l periods she will be paid $V = \$(1+r')^l K$ if the bank has that amount of money on hand to pay all the people who want to withdraw at that time. If not, it pays them an equal share of what it has on hand.

This scenario defines a game. In this game nature makes the first move and selects a bank where all the money is deposited. The type of bank is chosen randomly and is not revealed to the agents; they only know the distribution. When played in the normal form, this game has a strategy set consisting of the four integers $\{1, 2, 3, 4\}$ representing the four time periods at which money can be withdrawn and the expected payoff function,

$$E\pi_{it} = E_b(\pi(t, n_1, \dots, n_t, b, r', 6K)) \quad (2.1)$$

where b is the randomly selected bank and the expectation is over five possible banks selected randomly from a uniform density $f_b = 1/5$, $b = 1, 2, 3, 4, 5$.

This payoff function has the following interpretation: It defines the expected payoff to player i removing her money in period t depending on the time period t the money is withdrawn, the vector of withdrawals up until and including time t , denoted by, $n_1, \dots, n_t$ where, n_t is the number of players withdrawing in period t , the density function over banks, the promised rate of return and the total amount of money deposited in the bank to start the model going in period 0, $\$6K$. Note that the expectation is taken over banks which

is a random variable generated by the uncertainty in the banking system.

When played in extensive form, play takes place sequentially so that each agent has to decide period by period if he or she wants to remove his or her money. Here however, we can specify several different informational varieties. For example, the extensive form can be played such that after each period no information is given to the players as to how many people withdrew their money and therefore what they received if and when they did. This form is equivalent to the simultaneous form and we call it the Low-Information Sequential Form. Alternatively, we can specify a high-information version of the game in which after each period both the number of people who withdrew their money and the amount of money they received is revealed. This High-Information Sequential Form allows an expanded strategy space since here players can condition their withdrawal strategy both on how many people removed their money and what they received. In other words, history dependent strategies are available here.

2.3 Experimental Parameterization, Procedures and Design

To perform our bank run experiment groups of six subjects were recruited and asked to arrive at the experimental laboratory of the Center for Experimental

Social Science at New York University. They were recruited from undergraduate economics classes at New York University. They were paid \$5 for showing up on time and earned on average about \$22 more in the 1.5 hour experiment.

Instructions were administered on their computer monitors. The instructions explained the problem and they were handed tables presenting their payoff function³. These tables told them what their payoff would be conditional on any scenario (or vector) of withdrawals and also conditional on each of the five banks their money might be in. It also listed their expected payoff for each scenario given the probability function defined over the banks. To test their knowledge of payoff table use, the instructions present them a series of quizzes to make sure they know how to use the payoff tables⁴. In addition, to help even more, subjects could use an on-screen "calculator" which was presented in a window on their screen if they clicked a button labeled "calculator". This calculator allowed them to enter any scenario of withdrawals into the computer and would tell them what expected payoff each hypothetical subject would get under that scenario. (Subjects used this calculator both before the first round of the experiment and during it. They also referred to their payoff tables repeatedly).

To perform our experiment we used several specific parameterizations of

³Instructions and payoff tables are presented in the Appendix.

⁴Actually subjects became quite comfortable in using the payoff tables.

our model. More precisely, in the experiment, just as in our model, there are 5 potential banks and 6 agents. r' , the promised rate of return, is kept constant at 12% while the average rate of return r^* (i.e. the rate of return of the mean bank B_m) varied from $r^* = .07$, to $r^* = .08$ and to $r^* = .14$. In addition, we ran the experiment under several informational conditions. Each combination of r' and r^* was run in the simultaneous or normal form and under the High and Low-Information Sequential forms. We also ran a set of experiments where information was asymmetrically distributed or where two of the six subjects were informed about the quality of the bank their money was deposited in before they had to make withdrawal decisions while four were uninformed. This was done using the $r^* = .08$ mean bank rate since with $r^* = .08$ the equilibrium to our symmetric information experiment is unique and we can make a clean measurement of the impact of asymmetric information. Finally, we ran a set of experiments where partial deposit insurance existed in an effort to compare the behavior of subjects with and without such insurance.

Since our interests in this paper were both theoretical and policy oriented, we chose our parameters carefully. What we wanted were parameter values that would determine both an “early” and a “late” equilibrium. In the “early-equilibrium” experiment ($r^* = .07$) subjects are faced with a greater risk of loosing their deposits if they remove their money too late since there was no bank that could pay all of the subjects their promised amount if they all chose

to remove their funds in the same period. In addition, no matter what the pattern of withdrawals is, (even in equilibrium) there will always be some subjects (may be all) who will not be able to get his or her promised amount in the period they withdraw it. Hence the equilibrium in this treatment was for all subjects to either remove their money in period 1 or all to remove their money in period 2. In contrast, in the late-equilibrium experiment ($r^* = 0.14$), where all subjects either remove their money in period 3 or all remove their money in period 4, such risks were lessened since three out of five banks could pay the promised amount if all money was withdrawn at the same time (even in the last period).

We wanted such “early” and “late” equilibrium experiments since, for policy purposes, we wanted our bank insurance and informational interventions to be able to diminish the severity of bank runs by shifting withdrawals from early to late periods. This was accomplished by setting $r^* = .07$ which as we see in Table 7, determines an equilibrium where either “everybody moves in Period 1” or “everybody moves in Period 2” and by setting for $r^* = .14$ where either “everybody moves in Period 3” or “everybody moves in Period 4”. We chose to have 6 people, 5 banks and 4 periods because those were the smallest such numbers we could use that provided sufficient uncertainty and room for meaningful dynamics (3 period model essentially only allows two withdrawal choices and hence is not unlike the standard static model, while 5 banks allow

us sufficient flexibility on interest rates to define the variety of equilibria we need).

Finally we set $r^* = .08$ for the incomplete information experiments since with $r^* = .08$ the equilibrium to our symmetric information experiment is unique and we can make a clean comparison of the impact of insiders on withdrawal behavior by comparing the two treatments.

In our experimental design, while we run the bank-run experiment for 21 rounds we pay high stakes in the first round and low stakes in the remaining 20 rounds. More precisely, the first round is worth 20 times as much as any of the remaining rounds. We do this because bank runs, while important, are rather rare occurrences. In one's lifetime if one lived through one or two bank runs that would be considered many. As a result, while subjects may learn to reach an equilibrium after 20 rounds of play, in the real world people rarely have as much experience with bank runs. Therefore, we pay high stakes for the first round of the experiment and allow the remaining low stakes rounds to tell us something about learning.

We feel that this is an important feature of our design where we allow subjects to play for high stakes over a horizon that matches the one found in the real world yet lets them learn for low stakes later on in the experiment.

2.4 Some Quick Theory

Since our experimental bank run game has discrete strategy sets and a finite number of players, we can search for all pure strategy equilibria by exhaustively checking all strategy combinations. The equilibria we find by doing this are presented in the far right hand column of Table 7⁵.

As we can see from Table 7, our bank run model, with its present parameterization, yields equilibria that have certain distinct features. First, they involve all agents moving at exactly the same time (they are symmetric with respect to players). Second, if there are multiple equilibria, then they are adjacent i.e., either all remove their money in period 2 or all remove in period 3 or all remove their money in period 1 or all in period 2 etc. (This rules out multiple equilibria where, for example, either all people remove in period 1 or all remove in period 3). Third, as the mean rate in the industry, r^* increases, agents remove their money later. So if one were to take r^* as a cyclical indicator (average rate of return from investments in the economy when the bank crisis hits), we would expect money to be removed later in a bank run when it occurs during good times than during bad times (the run is less severe). Fourth, in our experimental parameterization, the equilibria for the Simultaneous form game remain the only pure strategy equilibria for both the Low

⁵The program used to calculate these equilibria is available from the authors.

and High-Information Sequential form games so we should not expect information to affect behavior in these experiments. Finally, although not indicated in Table 7, in our experiments when there is asymmetric information and where insiders exist, the expected length of time that money stays in the banking system in a separating equilibrium of the model increases, meaning that bank runs are less severe when insider information exists.

These results are summarized by the following propositions that will serve as the basis for the hypotheses we will test in Section 5.

Proposition 1 *Equilibrium Characterization:* *The pure strategy equilibria to all versions of the bank run game tested in our experiments, involve all subjects removing their money at the same time.*

P roof. Since the strategy space for our game is finite, we can substantiate this characterization by enumerating all pure strategy configurations in all of our experimental parameterizations and exhaustively checking them for equilibria. Such a process confirms Proposition 1. ■

This proposition basically says that at any equilibrium of our experimental game, all subjects should remove their money at the same time. There are no asymmetric pure strategy equilibria in which subjects remove at different times.

To provide some intuition for Proposition 1, we start by noting that for

any pair $\{r^*, r'\}$ there is a critical number c^* such that the first c^* people who remove their money in any period receive the promised amount in the period they withdraw. For the case where $r^* = .14$ and $r' = .12$, $c^* = 5$ and we will use this case to provide our intuition.

First, it should be clear that in any equilibrium there can be no gaps in withdrawal times (i.e. an equilibrium must be an "adjacent equilibrium" where either people withdraw their funds at the same or adjacent periods.) To illustrate this suppose $n = (n_1, n_2, n_3, n_4)$, is the vector of withdrawals (n_t being the number of subjects withdrawing in period t) and suppose there is a gap, i.e., $(n_t, 0, n_{t+j})$ with n_t and $n_{t+j} > 0$. Since $n_t \leq c^*$ by construction, players who withdraw in period t get their promised return. Hence there is an incentive for one of them to deviate to the next period (move into the gap) remove their money later and get their promised return one period later after it has compounded for another period. Hence no gap can exist.

Next, there can be at most two adjacent periods in which people withdraw their funds. To demonstrate this, suppose this is not true. Let (n_{t-1}, n_t, n_{t+1}) , be the number of subjects (greater than 0) who withdraw in period $t - 1$, t and $t + 1$ respectively. We know (because $c^* = 5$) that players who withdraw in period $t - 1$ and t get their promised returns. Therefore one of the players who withdraws in period $t - 1$ has an incentive to deviate to period t and get more.

Our next step is to show that subjects who move early in any adjacent equilibrium (if one exists) receive a higher payoff than those withdrawing later. To show this, again, suppose this is not true. Then one of the players who moves in period t would deviate to $t + 1$. Now when he makes this deviation he brings with him his promised return of period t , which is now allowed to compound one more period. By this deviation to period $t + 1$, then, the subject gets a convex combination of what players in period $t + 1$ were getting and the promised of period t compounded one more period, which is greater than the promised of period t . Therefore any configuration where subjects in adjacent periods get more in period $t + 1$ than those in period t cannot be a candidate for an equilibrium.

Our final two steps are to show that if an adjacent equilibrium exists it must have 5 subjects withdrawing in period 3 and 1 in period 4 and then to show that even this is impossible.

To demonstrate the first assertion, say that we have an adjacent equilibrium where there is more than one subject withdrawing in period $t + 1$. We know that players who move in period t receive more than those in period $t + 1$. We also know that since there are less than 5 of them, they are receiving their promised payoff. Hence one of the subjects who moves in period $t + 1$ would have an incentive to deviate to period t and get the promised payoff of period t which is greater than what he was getting in period $t + 1$. So the only adjacent-

equilibrium configurations must have 5 subjects removing first and 1 subject following in the next period. Hence, the only candidates for an equilibrium are the three vectors, $n^1 = (5, 1, 0, 0)$, $n^2 = (0, 5, 1, 0)$, $n^3 = (0, 0, 5, 1)$. n^1 and n^2 cannot be equilibria, however, since there is an incentive for the subject who removes his money alone to withdraw it later since that would allow him to get the same monetary payment but compounded for one or two more periods. So, the only candidate for adjacent equilibria is the vector $n^3 = (0, 0, 5, 1)$. From inspection of the payoff table, however, we can see that this cannot be an equilibrium since the subject who goes in period 4 gets an expected payoff of 11.23 while if he deviates to period 3 her expected payoff would be \$13.34. Hence if an equilibrium were to exist in this game it must involve all subjects removing at the same time.

Proposition 2 *Comparative Statics:* *For all parameter values of our experimental design, if we hold the promised rate of return by the banking industry constant, in equilibrium, money stays in the bank longer the higher the mean rate of return, r^* , is in the banking industry.*

P roof. As with Proposition 1, since the strategy space for our game is finite, we can substantiate this result by enumerating all pure strategy configurations in all of our experimental parameterizations and exhaustively checking them for the appropriate comparative static results. See Table 7. ■

We can see these characteristics illustrated in Table 7. For instance, note that in the $r' = .12, r^* = .07$ experiment subjects should, in equilibrium, remove their money relatively early (period 1 and 2) since the mean return in the banking industry is low, while in the $r' = .12, r^* = .14$ experiments, subjects, in equilibrium, remove their money later (periods 3 and 4) since the banking industry, on average, is better. This means that bank runs should be less severe when a banking crisis develops in relative good times. Clearly, as the mean return in the banking industry, r^* , increases, for any given r' , it pays to keep your money in the banking system longer since, for any vector of withdrawals, the probability that the bank will be solvent at any time increases.

Proposition 3 *Informational Invariance:* *For any configuration of r^* and r' , a withdrawal vector $a = (a_1, a_2, a_3, a_4)$ such that $a_1 + a_2 + a_3 + a_4 = 6$, is an equilibrium to either the High or Low- Information Sequential Form Game if and only if it is an equilibrium to the Simultaneous Form Game.*

P roof. See Appendix B. ■

This proposition states that no new equilibria are introduced into the analysis when we move from the Simultaneous form to the extensive High-Information (or Low-Information) form of our laboratory bank run game. If a configuration is an equilibrium for the Simultaneous game it is also an equilibrium to the sequential form and visa versa.

Proposition 4 *Insider Information and Bank Run Severity:* *Let $ELSI$ and $ELAI$ stand for the expected length of time money remains in the banking system at any equilibrium of our bank run game with symmetric information (SI) and any separating equilibrium for the bank run game with asymmetric information (AI) where $r^* = .08$. Then, $ELAI > ELSI$.*

P roof. See Appendix B. ■

This proposition implies that the presence of insiders is welfare improving since in any separating equilibrium of our bank run game with asymmetric information, money is withdrawn later than it is in the equilibrium to the same game without insiders or where information is symmetric.

2.5 Results

Our model and experimental design generate a number of hypotheses, which we will investigate shortly. Some of these hypotheses come directly from the theory but some are behavioral and outside the predictions of the model. In our presentation we will mix our discussion of the predictions of the theory with the policy implications we see in the behavior of our subjects. To test our theory we will initially concentrate on behavior in the big-stakes first round of the experiment run with symmetric information (no insiders). We do this, as stated before, since bank runs are not events that occur often in one's life and

hence we cannot look at long run convergent behavior as the basis upon which to make policy recommendations. Later we will comment on learning as well as discuss the results of our asymmetric information experiments.

2.5.1 Equilibria

We will phrase many of our hypotheses in terms of their consequences for the severity of bank runs since that is the focus of our paper.

Hypothesis 1: Equilibria

The behavior observed by our subjects in the first round of the Simultaneous, Low and High Information treatments of our bank run experiment is consistent with the behavior predicted by the equilibria of the model.

Evidence

Support for this hypothesis is mixed. In Figures 4a-4f you see the histograms of the actions chosen by subjects in the first round of our bank run experiment in the Simultaneous, Low-Information Sequential and High-Information Sequential forms of the game for the $r' = .12, r^* = .07$ (Figure 4a-4c) and $r' = .12, r^* = .14$ (Figure 4d - 4f) treatments. In addition, Figures 4g-4i and 4j-4l presents the same data but aggregated into early, (periods 1 and 2) and late (periods 3 and 4) behavior. In the $r^* = .07$ experiment, all early actions

are equilibrium actions since they are consistent with some Nash equilibrium. The same is true for late actions in the $r^* = .14$ experiment. We present these figures because with multiple equilibria it may be too much to ask that subjects solve the coordination implied by the theory in the first round of the experiment. However, we can check at least that they acted in accordance with some equilibrium. Hence all early actions in the $r^* = .07$ experiment, we will call "equilibrium" actions, as we call all late actions in the $r^* = .14$ experiment.

Note that if the predictions of the theory were substantiated we would see all observations either on periods 1 and 2 ($r^* = .07$) or 3 and 4 ($r^* = .14$) depending on the parameters of the treatment. This is basically true for the $r' = .12, r^* = .14$ case. Here, while subjects are supposed to remove their money late, in periods 3 and 4, we see that 73%, 75% and 92% actually do so in the Simultaneous, Low and High-Information Sequential treatments respectively. This behavior is quite close to that predicted by the theory especially when our subjects have not had a chance to learn the equilibrium. The same is not true, however, for the $r' = .12, r^* = .07$ experiment. While the theory predicts no late withdrawals in periods 3 and 4 we see that 50%, 67% and 58% of the subjects remove their money during these periods in the Simultaneous, Low and High-Information Sequential treatments respectively. Hence there appears to be a difference in behavior in these two cases. Information

Proposition 3 states that the equilibria of the bank run game for any configuration of parameters should be invariant to the form in which the game is played. Hence, we should not detect any difference in the behavior of subjects across experiments with the same parameters but different informational conditions. If a difference occurs, then we must ascribe it to extra-theoretical considerations.

Hypothesis 2: Information

For any given set of parameters r' and r^* , there is no difference in the play of our bank run game as informational treatments vary.

Evidence

This hypothesis is motivated by behavioral considerations and not theoretical ones. As Proposition 3 states, there should be no difference in the behavior of subjects when they play the Simultaneous game as opposed to the Low or High-Information Sequential Game. If a difference occurs, then we must ascribe it to extra-theoretical considerations.

In the real world we view bank runs as occurring in a High-Information Sequential form. Basically you wake up one morning, read the papers, and realize that there is a financial crisis stirring. On your way to work, you see a line at the bank and later in the day you hear from your friends that they tried to withdraw their funds but could not. The next day you run to the bank and

withdraw your money. In other words, we think that the most natural way to model bank runs is using the High Information Sequential form of the game. Therefore, if differences do occur as a result of informational treatments, then we would think that those derived from the High-Information Sequential play treatments have the greatest external validity. Consider Figures 4a-4l.

As we can see in our $r^* = .07, r' = .12$ experiment there is no significant difference in the withdrawal behavior of our subjects across any of the informational treatments at, at least the 10% level. This is confirmed by a series of bilateral χ^2 tests run on the early (periods 1-2) and late (periods 3-4) data⁶.

The same cannot be said for the $r^* = .14, r' = .12$ experiment, however. Here there seems to be a clear tendency for subjects to remove their money later when the bank run game is played in the High-Information Sequential form when compared to the Simultaneous form experiment. In fact, of the 24 subjects only 8% removed their money in period 1 or period 2 in this experiment as compared to 27% and 25% for the Simultaneous and Low-Information Sequential forms of the game. These differences are significant at the 8% level using a χ^2 test only for the comparison between the Simultaneous and Sequential High-Information form⁷.

⁶Impact of information on Behavior for $r^*=7\%$:

	Seq. Low	Seq. High
Simul.	$\chi^2 = 2.55$ ($p > .10$)	$\chi^2 = 0.455$ ($p > .10$)
Seq. Low		$\chi^2 = 2.55$ ($p > .10$)

⁷Impact of information on Behavior for $r^*=14\%$:

Bank runs appear to be less severe when subjects have more information about what other people have done. A logical consequence of this result is that wider dissemination of information about an evolving crisis may be helpful in slowing it down if people know in advance that they will have access to that information.

In his classic, *Lombard Street*, Bagehot (1873) argues that during times of panic, transparency on the management of the crisis may reduce uncertainty and may have a calming effect on financial markets. In that sense, our result is consistent with Bagehot's suggestion.

One reason why this may be true is that if people know that they will learn about the progress of a crisis as it proceeds, then they may decide to take a "wait and see" attitude and withdraw their money when they see the first bit of trouble. If everyone does this, then the crisis is less severe. Also, we know from other studies, see Schotter, Weigelt and Wilson (1994) and Cooper and Van Huyck (2001) that play of the same game in the normal and extensive form may not be equivalent because, perhaps, these two forms highlight different features of the decision problem.

	Seq. Low	Seq. High
Simul.	$\chi^2 = 0.019$ ($p > .10$)	$\chi^2 = 2.97$ ($p < .08$)
Seq. Low		$\chi^2 = 2.40$ ($p > .10$)

2.5.2 Bank Run Severity and the Business Cycle

The comparative static results tested in our experiment provide an answer to a simple question: Are bank runs less severe when they occur in good as opposed to bad economic times? Put differently, should money remain in the banking system longer in the $r^* = .14$, $r' = .12$ as opposed to the $r^* = .07$, $r' = .12$ experiment? Our theory says yes since the equilibrium of the $r^* = .14$, $r' = .12$ experiment suggest removal in periods 3 or 4 while in the $r^* = .07$, $r' = .12$ experiment removal is earlier (period 1 or 2). This yields the following null hypothesis.

Hypothesis 3: Comparative Statics

Under any information condition, subjects remove their money later in the $r^* = .14$, $r' = .12$ experiment than they do in the $r^* = .07$, $r' = .12$ experiment.

Evidence:

Our data give mixed support for this hypothesis. Using a set of bilateral Wilcoxon tests to compare the mean withdrawal times in the first period of our $r^* = .07$ and $r^* = .14$ experiments, we find that there is a statistically significant difference in the withdrawal times of subjects between the $r^* = .07$ and the $r^* = .14$ experiments only when the game is played in the High-Information Sequential or Simultaneous versions ($z = -3.32$, $p = 0.0005$ in the Sequential

High-Information $r^* = .07$ vs $.14$ comparison and $z = -2.57$, $p = .0052$ for the Simultaneous $r^* = .07$ vs $.14$ comparison). For some reason there was no significant difference when comparing the Sequential Low-Information experiments. More precisely, note that while in the High-Information Sequential $r^* = .14$ treatment only 8% of the subjects remove their money in rounds 1 or 2 (early withdrawals) and 92% withdraw it in rounds 3 and 4 (late withdrawals), in the $r^* = .07$ High-Information Sequential treatment these percentages are 42% and 58% respectively (see Figures 4i and 4l). In other words, there is a clear tendency to remove one's money later (less severe bank runs) when r^* changes when the game is played in the High-Information Sequential Form. (Note that the fractions of early withdrawals is not that different when we compare the Sequential Low-Information $r^* = .07$ and $r^* = .14$ treatments, 33% vs 25%, respectively).

We find these results important from a theoretical and policy point of view. First, theoretically we should detect differences between the behavior of our subjects as we vary r^* . The fact that the theory predicts behavior best in the High-Information Sequential version of the experiment is important since we consider that most empirically relevant form of the game. From a policy point of view this result implies that during the course of a bank run it is better, rather than worse, to offer information as to how people are doing when they withdraw their money as long as people know, ex ante, that they will have

access to this information as it is revealed.

2.5.3 Deposit Insurance

As stated before, we are interested in the type of intervention that can dampen bank runs. While full insurance is almost certain to do so, it can be quite costly and can create moral hazard on the part of the banks since depositors feel no obligation to monitor how their bank runs its affairs⁸.

In our deposit insurance experiments we imposed a 50% and a 20% insurance rate in two experiments so that no subject could lose more than 50% or 80% respectively, of what was owed them. We imposed this on the $r^* = .07$, $r' = .12$ experiment since it is in that experiment that subjects were most at risk and were supposed to remove their money early as opposed to late. We also used the High-Information Sequential version of the experiment since, as we have said before, we consider that one to be the most empirically relevant.

We find, using a simple linear regression model, that withdrawal times are positively related to the level of deposit insurance, although the distribution of withdrawal times differs from the no-insurance treatment only for the 50% case. To demonstrate this we present Table 8 and Figure 5.

Note that in Table 8 while 42% of subjects remove their money early (pe-

⁸Bhattacharya, Boot and Thakor (1998) is a comprehensive survey on bank regulation that discusses the alternatives for full deposit insurance.

riod 1 or 2) the experiment with no insurance, only 25% and 17% of the subjects removed their money in these rounds in the 20% and 50% insurance experiments, respectively. These differences, between insurance treatment and non-insurance treatments, are statistically significant at the 5% using a χ^2 test for the comparison between the early-late data of the no-insurance and the 50% insurance treatment only ($\chi^2 = 3.63, p \approx 0.05$). It appears as if 20% insurance is too small to affect behavior, however. Note also that issuing 50% insurance totally eliminates period 1 withdrawals.

When we run a simple OLS regression of the withdrawal period on the percentage of insurance (0%, 20% or 50%) for the first-round data pooled across all of the experiments where $r' = .12$ and $r^* = .07$, we find that insurance has a positive and significant impact on the withdrawal time⁹. In other words, as we increase the level of insurance in our experiments subjects tend to withdraw their money later and later.

These results and those discussed above lend support to the view that full (100%) deposit insurance is not necessary to dampen bank runs and hence may be inefficient.

⁹ Impact of Insurance on Withdrawal Times				
	Coefficient	Std. Error	z	p
constant	2.549	.124	20.50	.000
insurance	.800	.400	2.00	.049
$n = 72, R^2 = .054$				

2.5.4 Asymmetric Information

Probably our most interesting results are derived from our asymmetric information experiments. In these experiments, as discussed above, we informed two subjects before each round about the identity of the bank their money was invested in, while the other four received no information. Hence, in each round there were two informed and four uninformed subjects with the same two people always functioning as the informed subjects. Each round the bank was drawn randomly in an *iid* fashion.

While there are many possible separating equilibria for this model in which the informed subjects move first knowing which bank their money is invested in and then the uninformed, seeing what the informed have done, move later, they all share one important property which is that all separating equilibria are welfare improving when compared to the (unique) equilibrium of our $r^* = .08$, $r' = .12$ bank run game played with symmetric information (where everyone is uninformed). This is equivalent to saying that in any separating equilibrium of the asymmetric information game, on average, money stays longer in the bank. (Remember, when $r^* = .08$ and $r' = .12$, all subjects remove their money in period 2 (see Table 7)). The reason here is that since the strategies of the uninformed are conditional on the actions of the informed, and since the informed know this and it is in everyone's interest to keep their money in

the bank as long as possible, the informed are able to wait to withdraw their money even when they know that the bank is a bad one. The uninformed, in equilibrium, are willing to wait since they get more money, on average, by removing their money later even if it is after the two informed subjects remove theirs.

We are interested in several aspects of this asymmetric information game. First, we are interested in finding out if it is true that welfare increases in the presence of asymmetric information. Second, we are interested in seeing if people follow a separating equilibrium in that the uninformed wait until the informed remove their money and the removal times of the informed basically are consistent with some separating equilibrium.

Withdrawal Times

Figure 6 presents the histograms of first round removal times for our Asymmetric Information and the Symmetric Information, $r^* = 8$, $r' = .12$ experiments.

Note that the most dramatic difference between the two experiments is the difference in the frequency of period 4 withdrawal times with 21% more withdrawals in the asymmetric experiment. On average, money remained in the bank longer in the asymmetric information experiment than in the associated symmetric information no-insider experiment. For example, on average, across all sets of experiments using $r^* = .08$ and $r' = .12$, in the first round

money stayed in the bank, on average, for 2.83 periods in the no-insider experiments while it stayed there for 3.25 periods in the asymmetric-information experiments. A Wilcoxon test run to test the hypothesis that these withdrawal times came from the same population against the one sided alternative that money is withdrawn later in the asymmetric-information experiment, rejects the null at the 3% level of significance ($z = -1.871$, $p = 0.030$). An important feature of the experiments with insiders is that for better banks, on average, money stayed longer in the banking system. Therefore, with asymmetric information, runs were more severe when the chosen bank was not performing well, that is, runs were correct runs on average. We can see this if we look at the average time money stayed in the bank for the data pooled over the 21 rounds¹⁰¹¹.

Withdrawal Strategies

We are interested in knowing if subjects followed a separating equilibrium in this experiment. Such equilibria have a number of characteristics. Most impor-

¹⁰ Average time money stayed in the bank for each bank in the asymmetric information experiments.

	Average
Bank 1	2.73
Bank 2	2.85
Bank 3	3.02
Bank 4	3.11
Bank 5	3.23

¹¹ Saunders and Wilson (1996) discuss the role of informed depositors in the bank runs during the Great Depression.

tantly, informed agents should make their withdrawal choices by conditioning on the bank. Second, uninformed subjects should make their withdrawal choice by conditioning on the actions of the informed.

Confirming that informed subjects followed a separating equilibrium involves estimating their strategy functions. For example, we are interested in the withdrawal times of informed subjects conditional on the bank announced to them in any round of the experiment. To estimate this relationship we ran a set of multinomial logit regressions - one for each subject. In these regressions the dependent variable was a discrete variable taking on values of 1,2,3 or 4 depending on the period in which money was withdrawn. The right hand side, independent variable, was simply the bank rate realized in that period.

While the bank rate variable was only significant in about half of our subject regressions, all the signs were positive indicating a positive relationship existed. Of course with only 21 observations per subject and discrete right-hand and left-hand variables we are not surprised that a number of the coefficients were not significant.

When our multinomial logit regression is run on the pooled data from all informed subjects, however, we find a highly significant and positive coefficient for the bank rate variable indicating a positive relationship between the bank rate and the probability of removing money later¹².

¹²Multinomial Logit Results for Withdrawal Behavior of Informed Subjects

Perhaps a more direct way to show that informed subjects followed a separating equilibrium can be seen in Figure 7. This figure shows, for any realized bank, the withdrawal times of informed subjects. All observations are pooled over all informed subjects and over the entire length of the experiment.

If a separating equilibrium were evident in the data, then for informed subjects, we should expect to see the distributions of withdrawal times shift as the realized bank gets better and better. (We actually expect it to shift to the right). The mean withdrawal times should also increase. As we see in Figure 7 this is in fact the case. For example, the modal withdrawal time is period 2 when the bank is Bank 1, period 3 when it is Bank 2 or 3, and period 4 when it is Bank 4 or 5. Further, using a Wilcoxon test we can reject the hypothesis that withdrawal times were identical for any pair of adjacent banks. More precisely, a set of binary Wilcoxon tests¹³, testing for equality of mean withdrawal times rejects the hypothesis that these times are equal for

Period**	Coefficient*	Std. Error	z	p
2	.6412	.2377	2.70	.007
3	.7932	.2366	3.35	.001
4	.8286	.2365	3.50	.000

n = 168, Pseudo R2=.2810, Log Likelihood = -167.44

* Coefficients indicate the impact of an increase in the bank rate on the probability of withdrawal in any given period.

** Period 1 is the comparison period.

¹³One-tailed Wilcoxon test results:

	z	p
Bank 1 vs. 2	-4.76	.00
Bank 2 vs. 3	-1.46	.07
Bank 3 vs. 4	-4.34	.00
Bank 4 vs. 5	-3.07	.0005

comparisons of Bank 1 vs. Bank 2, Bank 3 vs. Bank 4 and Bank 4 vs. Bank 5 at at least the 1% level in favor of the one tailed alternative that subjects withdrew later the better the bank. (For Bank 2 vs. Bank 3 the difference is significant at the 7% level). Further, calling banks 3, 4 and 5 good banks and banks 1 and 2 bad banks we can easily reject the hypothesis of equality of mean withdrawal times across these categories in favor of the one-tailed alternative that informed subjects withdrew their money later when good banks were realized ($z = -8.5786$, $p \approx 0$). Finally, note that when Bank 5 is announced informed subjects remove their money in period 4, 97% of the time and do so 68% of the time when Bank 4 is announced. No informed subject removes her money in period 4 when Bank 1 is announced.

With respect to the uninformed subjects, we support the hypothesis that these subjects were engaged in separating equilibrium-like behavior by showing that their behavior changed when they were in the presence of informed subjects in comparison to how they behaved in our symmetrically informed $r' = .12$, $r^* = .08$ experiment where, in essence all subjects were uninformed. We would expect that in the asymmetric information experiment they would condition their withdrawal on the behavior of informed subjects and hence withdraw later. To illustrate that this is the case consider Figure 8 which presents the histograms of withdrawal times for all uninformed subjects in our asymmetric information experiment and all subjects in our symmetric $r' = .12$,

$r^* = .08$ experiment.

As we see, it is clear that uninformed subjects in our asymmetric information experiment withdraw their money later than those in the comparison symmetric information experiment. For example, while 87% of the subjects withdraw in period 3 and 4 in the asymmetric information experiment, only 67% of the symmetrically informed subjects do. A Wilcoxon test rejects the hypothesis of equality between the samples in favor of the one-tailed alternative that the mean withdrawal time of the uninformed subjects in the asymmetric information experiment is greater than the mean withdrawal time in the symmetric information experiments at the .0004 level ($z = 3.514$, $p \approx 0.0004$).

Perhaps a more direct way to make the point that uninformed subjects conditioned their withdrawal behavior on the actions of the informed is to use a counting metric. The idea behind this approach is that in any separating equilibrium no uninformed subject is ever expected to remove his or her money without seeing someone else remove theirs first. Using this fact we count the number of times that uninformed subjects withdrew their money before any one else did as opposed to waiting for at least one other person to do so. Whenever an uninformed subject was not the first to withdraw his or her money (i.e. if he or she withdrew at least one period after someone else) we counted that observation as supporting the separating equilibrium while any time an uninformed subject removed his money without anyone having done

so in previous periods, we counted that as evidence against the separating equilibrium hypothesis.

Using this approach we found that of the 356 removal decisions pooled over all experiments and all subjects, 215 were supportive of the separating equilibrium while 141 contradicted it. Using a binomial test we tested the null hypothesis that the removal times of uninformed were random (equally likely to be before or after someone else) against the hypothesis that uninformed subjects were more likely to remove their money after the informed (or at least after someone else had removed theirs). We were able to reject the null at the 1% level of significance ($z = 5.88$, $p < .001$).

Our final attempt to convince you that subject behavior in our asymmetric information experiments had the earmarks of a separating equilibrium comes a set of questionnaires we administered asking our subjects to describe their behavior in the experiment by writing down what type of strategies employed. From their responses it was clear that both the uninformed and the informed tended to use separating equilibrium-type strategies. Some of these reports can be found in the Appendix.

In summation, it appears as if the behavior of our subjects in the asymmetric information experiments we ran was consistent with the behavior of subjects following some type of separating equilibrium. Informed subjects clearly conditioned their withdrawals on the bank drawn while uninformed subjects

appeared to wait longer before withdrawing implying they were conditioning their withdrawal choice on the behavior of informed subjects. These stylized facts were supported by comments made by our subjects in post-experiment questionnaires.

2.6 Learning

As stated before, we do not consider learning a relevant subject for bank run experiments since few of us will ever have repeated experience with them in our lifetimes. One bank run or perhaps two may be all that anyone is likely to experience. However, we did run our experiments 21 times in an effort to see if the equilibrium predictions of our model had drawing power. Table 9 compares the withdrawal times of our subjects over the first and last five rounds of each experiment.

As you can see, the results of this comparison are mixed. Subjects in the $r^* = 0.14$ experiment do change their behavior over the 21 rounds when we compare their actions in the first and last 5 rounds. Here there is a clear tendency to move toward the equilibrium predictions and withdraw later in periods 3 or 4. These differences are significant using a Wilcoxon test and testing the null hypothesis of no change against the alternative of change in the direction of the equilibrium predictions (which in this case is to have the

withdrawal times move later in the last five rounds). In the $r^* = 0.07$ experiments we can only reject the null hypothesis of no change in the Sequential Low-Information treatment. These same tests indicate that withdrawal times are closer to the equilibrium withdrawal times for the 20% and 50% insurance experiments as well but there is no change in the $r^* = 0.08$ and Asymmetric Information experiments.

In short, it appears as if the feedback we gave subjects in this experiment was not sufficient to lead them to equilibrium behavior in a very consistent manner. Still, by and large there was a movement in the right direction.

2.7 Conclusion

This paper has tried to investigate the factors that determine the severity of bank runs and to point out possible policies that might help dampen them. We have demonstrated that in general the more information economic agents can expect to have about an ongoing crisis, i.e. the more they can expect to learn about the crisis as it develops, the more willing they are to restrain themselves in withdrawing their funds from banks once a crisis actually occurs. In addition, we have seen that deposit insurance, even of a limited type, can also help to diminish the severity of bank runs. This is important because full deposit insurance creates moral hazard on the part of bank managers since

their actions tend not to be monitored by depositors if their funds are fully insured. By offering only partial insurance, the hope is that not only will bank runs be less severe, but depositors will also be more vigilant in their monitoring of bank managers. Finally, we have seen that the presence of insiders who know the quality of the bank their money is invested in, is welfare increasing in the sense that when such insiders exist, subjects tend to withdraw their money later than they would if no such insiders exist.

Chapter 3

Information Contagion and Inter-Bank Correlation in a Theory of Systemic Risk

Joint with Viral Acharya

3.1 Introduction

The past two decades have been punctuated by a high incidence of financial crises in the world. In the period 1980–1996 itself, 133 out of 181 IMF member countries experienced significant banking problems, as documented by Lindgren, Garcia, and Saal (1996). Developed countries and emerging countries have been equally affected.¹ These crises have been empirically shown to be associated with high real costs for the affected economies. Hoggarth, Reis, and Saporta (2001) document that the cumulative output losses have amounted to a whopping 15–20% of annual GDP in the banking crises of the past 25 years. The restructuring and output losses have been as high as 50–60% of annual GDP in some emerging-market banking crises.

Understanding bank failure risk, and especially systemic failure risk — the risk that most or all banks in an economy will collapse together — is considered the key to predicting and managing such financial crises. Indeed, the issue of systemic risk amongst banks has long been attributed as the *raison d'être* for many aspects of bank regulation. Its causes, manifestations, and effects are however not yet fully understood. In this paper, we lay down a foundation that we hope will lead to an enhanced understanding of different forms of systemic

¹The most notable banking crises that affected developed countries include those in Finland (1991–1993), Japan (1992–present), Norway (1988–1992), Spain (1977–1985), Sweden (1991), and the U.S. (1987–1989). The banking crises that recently affected developing countries include those in Argentina (2001), Brazil (1999), Russia (1998), South East Asian countries (1997–1998), and Turkey (2000, 2001).

risk.

In particular, we examine liability side contagion, asset side correlation, and their interactions. Liability side contagion arises when the failure of a bank leads to the failure of other banks due to a run by their depositors or a liquidation of their liabilities. Asset side correlation across banks arises if they lend to similar firms or industries. The paper's goal is both positive as well as normative. On the positive side, we build a theoretical model whose assumptions and results are supported by empirical evidence. The normative aspects concern a welfare analysis of the costs and the benefits of systemic risk.

Recent models of contagion amongst banks include the work of Rochet and Tirole (1996), Kiyotaki and Moore (1997), Allen and Gale (2000), to cite a few. The primary focus of these studies is the characterization of contagion and financial fragility that arise due to the structure of inter-bank liabilities. By contrast, in our model there is no inter-bank linkage. Instead, we propose that systemic risk arises on the liability side of banks due to a revision in the cost of borrowing of surviving banks when some other banks have failed. Crucially, however, we also allow for systemic risk on the asset side of bank balance sheets. In particular, we show that banks choose a high correlation of returns on their investments by lending to firms in similar industries. The incentives for such action increase in the extent of systemic risk on the liability side. This

interaction of liability side and asset side systemic risk is an important and novel contribution of this paper.

In our model, there are two periods and two banks with access to risky loans and deposits. The returns on each bank's loans consist of a systematic component, say the overall state of the economy, and an idiosyncratic component. The nature of the ex-ante structure of each bank's loan returns, specifically their exposure to systematic and idiosyncratic factors, is common knowledge; the ex-post performance of each bank's loan returns is publicly observed. However, the exact realization of systematic and idiosyncratic components is not observed by the economic agents. Depositors in the economy are assumed fully rational, updating their beliefs about the prospects of the bank to which they lend based on the information received about not only that bank's loan returns but also those of other banks. Ex-ante, banks choose whether to lend to similar industries and thereby maintain a high level of inter-bank correlation, or to lend to different industries.

When a bank's loans incur losses, it may fail to pay its depositors their promised returns. Such failure conveys potential bad news about the overall state of the economy. Depositors of the surviving bank rationally update their priors and require a higher promised rate on their deposits. By contrast, if both banks experience good performance on their loans, then depositors rationally interpret it as good news about the overall state of the economy. Hence, they

are willing to lend to banks at lower rates. The borrowing costs of banks are thus lower if they survive together than when one fails. This is an information spillover of one bank's failure on the other bank's borrowing costs, and in turn on its profits. Indeed, if the future profitability of loans is low, the surviving bank cannot afford to pay the revised borrowing rate and fails as well. An information contagion results.

How do banks respond to minimize the impact of such liability side contagion on their profits? We argue that the response of banks manifests itself in *ex-ante* investment choices. The greater the correlation between the loan returns of banks, the greater is the likelihood that they will survive together; in turn, the lower is their expected cost of borrowing in the future and higher are their expected profits. Consequently, banks lend to similar industries and increase the inter-bank correlation. In other words, banks herd.² Intuitively, banks prefer to survive together rather than surviving individually. In the latter case, they face the risk of information contagion. By contrast, given their limited liability, bank owners view failing individually and failing together with other banks in a similar light. While information contagion sequentially transforms losses (or failure) at one bank into losses (or failure) at the other bank, greater inter-bank correlation increases the risk of simultaneous bank failure if

²Note that this form of *ex-ante* herding is different from *ex-post* or sequential herding that arises in typical information-based models of herd behavior. We elaborate on this difference in the Related Literature section.

the industries they lend to suffer a common shock.

We extend the model to allow the depositors of the failed bank to migrate to the surviving bank, if any exists. Intuitively, this captures a flight to quality phenomenon sometimes observed upon bank failures. Such flight to quality enables surviving banks to gain from the failure of another bank by scaling up their own operations. In this sense, flight to quality counteracts herding incentives by reducing the costs of banks from information contagion. Nevertheless, if the future profitability of loans is expected to be low, depositors may rationally choose not to lend even to the surviving bank. Formally, in the presence of flight to quality, the extent of ex-ante herding measured through inter-bank correlation is decreasing in the expected profitability of loans tomorrow. If the expected profitability of loans tomorrow is high, inter-bank correlation is low, and vice versa. Thus, we call this phenomenon the procyclicality of herding. Competition amongst banks for loans, whereby banks earn lower returns on loans if they lend to the same industry, gives rise to similar effects as flight to quality. Numerical examples illustrate the effect on procyclicality of the extent of systematic risk in bank loans and the relative likelihoods of good and bad states of the economy.

Finally, we conduct a welfare analysis. To do so, we allow for the possibility that banks can earn better returns by lending to some industries. In this setting, a potential welfare cost of herding arises when loans to more prof-

itable industries are passed up in favor of loans correlated with other banks. Compared to the *first-best* investments, herding can some times produce investments in firms and industries that are less profitable. Similarly, while flight to quality mitigates herding, it can sometimes be inefficient relative to the first-best: it gives banks competitive incentives to lend to different industries, even if a particular industry in the economy is more profitable for all banks.

In the context of our model, however, it is difficult to argue that herding is *constrained inefficient*. Herding is undertaken ex-ante to mitigate the ex-post costs that bank owners face from information contagion. Furthermore, these ex-post costs comprise social costs for the planner charged with maximizing the value of banking sector in the economy, specifically the sum of the values of bank equity values and deposits. Thus, taking financial intermediation as given, herding occurs in equilibrium only when it is also socially (constrained) efficient. We suggest possible mechanisms via which this result on the constrained efficiency of herding may be overturned. The regulatory assessment of systemic risk must thus take careful account of its different manifestations and delineate the social costs of systemic risk that exceed the costs to bank owners.

Section 3.2 discusses the related literature. Sections 3.3 and 3.4 present the model. Section 3.5 derives the information contagion. Section 3.6 demonstrates the herding behavior in response to information contagion, incorporates

flight to quality and includes some extensions. Section 7 presents the efficiency analysis. Section 3.8 discusses the incorporation of bank regulation. Section 3.9 concludes. Throughout the paper, empirical evidence is provided to support the theoretical results. All proofs are in the Appendix D.

3.2 Related Literature

De Bandt and Hartmann (2000) provide a comprehensive survey of the literature on systemic risk. Below we summarize the literature that is most relevant to this paper.

Several aspects of our model have roots in the documented empirical facts about banking crises. In models such as Diamond and Dybvig (1983), bank runs occur as sunspot phenomena. By contrast, banks in our model fail when depositors rationally update bank prospects with information gleaned from the realization of returns on bank loans. Gorton (1988), Calomiris and Gorton (1991) provide evidence that banking crises in the U.S. during the pre-Federal Reserve era, that is pre-1914, were preceded by shocks to the real sector and were not based purely on panic. The information spillover to other banks from a bank's failure is documented (Gorton, 1985, Gorton and Mullineaux, 1987) as the formative reason for the commercial-bank clearinghouses in the U.S., and eventually for the Federal Reserve. Chari and Jagannathan (1988),

Jacklin and Bhattacharya (1988) also model information-based bank runs. In their models, a depositor's decision to run on a bank leads to an information spillover on the decision of other depositors to run, either on the same bank or on others.

The empirical studies on bank contagion test whether bad news, such as a bank failure, the announcement of an unexpected increase in loan-loss reserves, bank seasoned stock issue announcements, etc., adversely affect the other banks.³ These studies have concentrated on various indicators of contagion, such as the intertemporal correlation of bank failures (Hasan and Dwyer 1994, Schoenmaker 1996), bank debt risk premiums (Carron, 1982, Saunders, 1987, Karafiath, Mynatt, and Smith, 1991, Jayanti and Whyte, 1996), deposit flows (Saunders, 1987, Saunders and Wilson, 1996, Schumacher, 2000), survival times (Calomiris and Mason, 1997, 2000), and stock price reactions (as discussed below).

Most empirical investigations of bank contagion are event studies of bank stock price reactions in response to bad news. These studies⁴ estimate a mar-

³If the effect is negative, the empirical literature calls it the "contagion effect." The overall finding is that the contagion effect is stronger for highly leveraged firms (banks being typically more levered than other industries) and is stronger for firms with similar cash flows. If the effect is positive, it is termed the "competitive effect." The intuition is that demand for the surviving competitors' products (deposits, in the case of banks) can increase. Overall, this effect is found to be stronger when the industry is less competitive.

⁴See Aharony and Swary (1983), Waldo (1985), Cornell and Shapiro (1986), Saunders (1986), Swary (1986), Smirlock and Kaufold (1987), Peavy and Hempel (1988), Wall and Peterson (1990), Gay, Timme and Yung (1991), Karafiath, Mynatt, and Smith (1991), Madura, Whyte, and McDaniel (1991), Cooperman, Lee, and Wolfe (1992), Rajan (1994), Jayanti

ket model for bank returns in a historical period before the event conveying bad news. Then the predicted value from the regression is compared with the actual value for a window surrounding the day of the event. Significant negative abnormal returns are regarded as evidence for contagion. These studies generally conclude that such reactions are rational investor choices in response to newly revealed information, rather than purely panic-based contagion.

The herding aspect of our paper is related to the vast literature on herding surveyed in Devenow and Welch (1996). In this literature, herding is often an outcome of sequential decisions, with the decision of one agent conveying information about some underlying economic variable to the next set of decision-makers. Herding, however, need not always be the outcome of such an informational cascade. It can also arise from a coordination game. In our paper (as also in Rajan, 1994), herding is a simultaneous ex-ante decision of banks to coordinate correlated investments (disclosures of losses). Overall, our paper is closest in spirit to Acharya (2000) who examines the choice of ex-ante inter-bank correlation in response to financial externalities that arise upon bank failures and “too-many-to-fail” regulatory guarantees. The channel of information spillover that we examine complements the channels examined in Acharya (2000). Finally, the welfare costs of herding examined here corre-

and Whyte (1996), Docking, Hirschey, and Jones (1997), Slovin, Sushka, and Polonchek (1999).

spond to bypassing superior projects by bank owners in a spirit similar to the welfare analysis in Scharfstein and Stein (1990), Rajan (1994).

Comprehensive empirical evidence on asset correlations of banks has not yet been undertaken. In a recent study, Nicolo and Kwast (2001) find that the creation of very large and complex banking organizations increases the extent of diversification at the individual level and decreases the individual firm's risk. However, this increased similarity introduces systemic risk. They use correlations of bank stock returns as an indicator of systemic risk potential,⁵ concluding their paper with the following: “[W]e know no studies of indirect interdependency, such as any tendency for loan portfolios to be correlated across banks.” Documentation of the correlations in loan portfolios of banks could provide potentially valuable information about the extent of systemic risk in a banking sector.

3.3 Model

We build a simple model that captures simultaneously (i) information spillover arising from bank failures, (ii) endogenous choice of correlation of bank returns,

⁵Specifically, Nicolo and Kwast (2001) find that stock prices of the biggest 22 U.S. banking organizations tended to increasingly move in lockstep during 1989–1999. The degree of correlation in stock price movements increased from 0.41 in 1989 to 0.56 during 1996–1999. They suggest on basis of this evidence that “Troubles at a single bank could easily generate investor perceptions of similar troubles at other big banks.”

and (iii) flight to quality.

First, we provide a general overview of the model. In our model, each bank has access to a risky investment, the return from which has a systematic and an idiosyncratic component. Only banks can invest in the risky assets. Banks make investments twice, that is, at two different times. Depending upon the realization of past bank profits, depositors assess the profitability of the risky asset of their bank and incorporate that information in the return they demand on their deposits. Depositors regard the failure of a bank as bad news about the systematic component of bank asset returns. As a result, the surviving banks must promise a higher return to the depositors. This negative effect constitutes an information spillover arising from a bank failure, which, in our model, affects the ex-ante choice of correlation in bank loan portfolios.

Formally, there are two banks in the economy, Bank A and Bank B , and three dates, $t = 0, 1, 2$. The timeline in Figure 9 details the sequence of events in the economy. There is a single consumption good at each date. Each bank can borrow from a continuum of risk-averse depositors of measure 1. Depositors consume their each-period payoff (say, w) and obtain time-additive utility $u(w)$, with $u'(w) > 0$, $u''(w) < 0$, $\forall w > 0$, and $u(0) = 0$. Depositors have one unit of the consumption good at $t = 0$ and $t = 1$. Banks are owned by financial intermediaries, henceforth referred to as bank owners. Bank owners are risk-neutral and also consume their each-period payoff.

All agents have access to a storage technology that transforms one unit of the consumption good at date t to one unit at date $t + 1$. In each period, that is at date $t = 0$ and $t = 1$, depositors choose to keep their good in storage or to invest it in their bank. Deposits take the form of a simple debt contract with maturity of one period. In particular, the promised deposit rate is not contingent on realized bank returns. Furthermore, since bank investment decisions are assumed to be made after deposits are borrowed, the promised deposit rate cannot be contingent on these investment decisions. Finally, the dispersed nature of depositors is assumed to lead to a collective-action problem, resulting in a run on a bank that fails to pay the promised return to its depositors. In other words, the contract is “hard” and cannot be renegotiated.

Banks choose to invest the borrowed goods in storage or in a risky asset. The risky asset is to be thought of as a portfolio of loans to different industries in the corporate sector, real-estate investments, etc. Investment by a bank in its risky asset at date t produces a random payoff $\tilde{R}_t$ at date $t + 1$. The payoff is realized at the beginning of date $t + 1$ before any decisions are taken by banks and depositors at date $t + 1$. The quantity $\tilde{R}_t$ takes on values of R_t or 0.

$$\tilde{R}_t = \begin{cases} R_t & \text{for } t = 0, 1. \\ 0 & \end{cases}$$

The realization of $\tilde{R}_t$ depends on a systematic component, the overall state of the economy, and an idiosyncratic component. The overall state of the economy can be *Good*(G) or *Bad*(B). The prior probability that the state is G for the risky asset is p .

$$State = \begin{cases} Good(G) & \text{with probability } p \\ Bad(B) & \text{with probability } 1 - p. \end{cases}$$

Even if the overall state of the economy is good (bad), the return on the risky asset can be low (high) due to the idiosyncratic component. The probability of a high return when the state is good is $q > \frac{1}{2}$: when the state is good, it is more likely, although not certain, that the return on bank investments will be high. The probability that the return is high when the state is bad is $(1 - q) < \frac{1}{2}$. Therefore, the probability distributions of returns in different states are symmetric. To summarize,

$$\Pr(\tilde{R}_t = R_t|G) = \Pr(\tilde{R}_t = 0|B) = q > \frac{1}{2}.$$

The resulting joint probabilities of the states and bank returns are given in Table 10. For simplicity, we assume that, conditional on the state of the economy, the realizations of returns in the first and second period are independent.

Crucially, banks can choose the level of correlation of returns between their

respective investments. We discuss this next. In order to focus exclusively on the choice of inter-bank correlation, we abstract from the much-studied choice of the absolute level of risk by banks.

3.3.1 Correlation of Bank Returns

Banks can choose the level of correlation between the returns from their respective investments by choosing the composition of loans that compose their respective portfolios. We will refer to this correlation as “inter-bank correlation.” For example, suppose that there are two possible industries in which banks can invest, denoted as 1 and 2. Bank A (B) can lend to firms A_1 and A_2 (B_1 and B_2) in industries 1 and 2, respectively. If banks choose to lend to firms in the same industry, specifically they either lend to A_1 and B_1 , or they lend to A_2 and B_2 , then they are perfectly correlated. However, if they choose different industries, then their returns are less than perfectly correlated, say independent. Allowing for a choice between several industries can produce a spectrum of possible inter-bank correlations.

To model this in a simple and parsimonious manner, we allow banks to choose a continuous parameter c that is positively related to inter-bank correlation and thus affects the joint distribution of their returns. The precise joint distribution of bank returns in different states of the economy as a function of the inter-bank correlation parameter c is given in Tables 11 and 12. As can

be verified from these tables, the probability of a high return for an individual bank remains the same in each state: q in good state, and $(1 - q)$ in bad state.

However, the joint probabilities vary with the correlation parameter c .

The maximum value of the correlation parameter c , denoted c_{max} , is q ; the minimum value of c , denoted c_{min} , is $(2q - 1)$. Restricting c to the range $[c_{min}, c_{max}]$ ensures that all probabilities are non-negative and not greater than one. The covariance, σ_{ab} , and the variances, σ_a^2 and σ_b^2 , of bank returns can be shown to be

$$\sigma_{ab} = R^2 [c(1 - q)^2 - 2(q - c)(1 - q)q + (1 - 2q + c)q^2], \quad (3.1)$$

$$\sigma_a^2 = \sigma_b^2 = q(1 - q)R^2, \quad (3.2)$$

where the time subscript has been suppressed. Hence, the correlation of bank returns is

$$\rho = \frac{\sigma_{ab}}{\sigma_a \sigma_b} = \frac{c(1 - q)^2 - 2(q - c)(1 - q)q + (1 - 2q + c)q^2}{q(1 - q)}. \quad (3.3)$$

It follows that $\frac{\partial \rho}{\partial c} = \frac{1}{q(1 - q)} > 0$. This justifies our decision to refer to the parameter c directly as the inter-bank correlation.⁶ In particular, the levels of

⁶Replacing c in the joint distribution of returns in Tables 11 and 12 by a function $f(c) \in [2q - 1, q]$, $f'(c) > 0$ produces qualitatively similar results. We have chosen the linear specification $f(c) = c$, since it produces the most transparent analysis.

inter-bank correlation for some specific values of c are:

$$\rho = \begin{cases} 1 & \text{when } c = q \\ 0 & \text{when } c = q^2 \\ 1 - \frac{1}{q} & \text{when } c = (2q - 1). \end{cases}$$

For example, in the welfare analysis in Section 3.7, we employ the two-industry example discussed above and restrict the choice of inter-bank correlation to $c = q$ when banks lend to the same industry, or $c = q^2$ when banks lend to different (independent) industries.

3.4 Investments

While the choice of inter-bank correlation is determined by backwards induction, it is easier for sake of exposition to first examine the investment problem at date 0. At date 0, both banks exist. By contrast, at date 1, depending upon the first-period return realizations, one or both banks might have failed.

3.4.1 First Investment Problem (date 0)

In the first period, both banks are identical. Hence, we consider a representative bank. Since depositors have access to the storage technology, their individual rationality requires that the bank offer a promised return r_0 that

gives depositors their reservation utility $u(1)$, assumed to be 1. Since $r_0 \geq 1$, it is straightforward to show that it is never optimal for banks to invest in the safe asset. Given their limited liability, banks maximize their equity “option” by investing all borrowed goods in the risky asset.⁷

Thus, depositors are paid the promised return r_0 only if the return on bank loans is high, that is R_0 . Because of the limited liability of banks, depositors get nothing when the return on bank loans is low. The probability of a high return on bank loans, denoted as α_0 , is

$$\alpha_0 = \Pr(G) \Pr(R_0|G) + \Pr(B) \Pr(R_0|B) \quad (3.4)$$

$$= pq + (1 - p)(1 - q). \quad (3.5)$$

The promised return r_0 that satisfies depositors’ individual rationality is thus given by

$$\alpha_0 u(r_0) = 1. \quad (3.6)$$

⁷Formally, suppose the bank invests θ units in the safe asset and $(1 - \theta)$ units in the risky asset. Then the payoff in next period is $\theta + (1 - \theta)\tilde{R}$. In the low state, this payoff equals θ which is lower than r_0 , the promised amount to depositors. Hence, bank owners receive no payoff in this case. In the high state, the bank’s payoff is $\theta + (1 - \theta)R$. Hence, bank owners receive $\max[R - r_0 - \theta(R - 1), 0]$, which is decreasing in θ . Hence, banks always choose $\theta = 0$. That is, they invest all borrowed goods into the risky asset.

Thus, it follows that the promised rate of return r_0 is

$$r_0 = u^{-1}(1/\alpha_0). \quad (3.7)$$

We assume that $R_0 > r_0$, as otherwise the problem at hand is rendered uninteresting. The payoff to the bank at date 1 from the first period investment, denoted as π_1 , is thus given by

$$\pi_1 = \begin{cases} R_0 - r_0 & \text{if } \tilde{R}_0 = R_0 \\ 0 & \text{if } \tilde{R}_0 = 0 \end{cases}. \quad (3.8)$$

The expected payoff to the bank at date 0 from its first-period investment, $E(\pi_1)$, is thus

$$E(\pi_1) = \alpha_0(R_0 - r_0).$$

Note that this expected payoff in the first period is independent of the choice of inter-bank correlation. Therefore, when banks choose the level of correlation, they examine the expected payoffs in different states of the world in the second period.

3.4.2 Second Investment Problem (date 1)

We assume that if the return from the first period investment is low, then there is a run on the bank, it is liquidated and it cannot operate any further. If the return is high, then bank owners make the second-period investment. Therefore the possible cases at date 1 are given as follows, where S indicates survival and F , failure:

SS : Both banks had the high return, and they operate in the second period.

SF : Bank A had the high return, while Bank B had the low return. Only Bank A operates in the second period. Bank B depositors invest their second-period goods in storage.

FS : This is the symmetric version of state SF .

FF : Both banks failed. No bank operates in the second period.

The possible cases are summarized in Table 13. Recall our simplifying assumption that realizations of returns in the first and second periods are independent, conditional on the true state of the economy. However, depositors have more information at $t = 1$ than they had at $t = 0$ to judge the profitability of the risky asset in which their bank invests: they have the realizations of the returns in the previous period for *both* banks. Depositors thus rationally update their beliefs about the profitability of the risky asset their bank invests

according to the information revealed by these returns.

Although a bank can have a high return in both states of the economy, that is in the good state as well as in the bad state, there is a systematic component in the probabilities of returns. Thus, the other bank's return is relevant information to assess the profitability of the risky asset of a given bank. Therefore, the cases SS (bank B survives) and SF (bank B fails) will have different continuation payoffs for bank A . In the next section, we compute the continuation payoffs of bank A for the case SS , and thereafter for the case SF .

Both banks survived (SS)

In this case, both banks operate for another period. Armed with the information of the survival of both banks in the first period, depositors can update the probabilities about the overall state of the economy using Table 11 and Table 12, to obtain

$$\begin{aligned}\Pr(G|SS) &= \frac{\Pr(G \text{ and } SS)}{\Pr(SS|G)\Pr(G) + \Pr(SS|B)\Pr(B)} \\ &= \frac{pc}{pc + (1-p)(1-2q+c)} \\ &= \frac{pc}{(1-2q)(1-p) + c}, \text{ and}\end{aligned}\tag{3.9}$$

$$\Pr(B|SS) = \frac{(1-p)(1-2q+c)}{(1-2q)(1-p) + c}.\tag{3.10}$$

Using these, depositors can calculate the probability of a high return for their bank in the second period, denoted as α_1 , as

$$\begin{aligned}
\alpha_1 &= \Pr(\tilde{R}_1 = R_1 | SS) \\
&= \Pr(G | SS) \Pr(\tilde{R}_1 = R_1 | G) + \Pr(B | SS) \Pr(\tilde{R}_1 = R_1 | B) \\
&= \frac{pc}{(1-2q)(1-p) + c} q + \frac{(1-p)(1-2q+c)}{(1-2q)(1-p) + c} (1-q) \\
&= \frac{pcq + (1-p)(1-q)(1-2q+c)}{(1-2q)(1-p) + c}. \tag{3.11}
\end{aligned}$$

As argued in the first-period investment, the individual rationality of depositors implies that the promised return, r_1^{ss} , should satisfy

$$\alpha_1 u(r_1^{ss}) = 1. \tag{3.12}$$

Therefore, we obtain that

$$r_1^{ss} = u^{-1}(1/\alpha_1). \tag{3.13}$$

Since α_1 depends on the inter-bank correlation c , we denote this borrowing rate as $r_1^{ss}(c)$.

Again, because of limited liability, banks honor their promises to depositors only when they have the high return. Thus, in this case the payoff to each

bank at date 2 from the second period investment, denoted as π_2^{ss} , is given by

$$\pi_2^{ss} = \begin{cases} R_1 - r_1^{ss} & \text{if } \tilde{R}_1 = R_1 \text{ and } R_1 > r_1^{ss} \\ 0 & \text{otherwise} \end{cases}. \quad (3.14)$$

Note that if $R_1 < r_1^{ss}$, then it is individually rational for depositors not to lend their goods to banks. Storage is preferred to deposits, since the highest return on loans is insufficient to compensate depositors for the risk of bank failure.

Only one bank survived (*SF* or *FS*)

This is the case where one bank had a high return, while the other had a low return and has been liquidated. Without loss of generality, we concentrate on the case *SF* where Bank *A* had a high return. From the symmetry of the joint probabilities in different states and using Tables 11 and 12, we obtain

$$\Pr(G|SF) = p.$$

Essentially, the good news about the economy from the performance of bank *A* is annulled by the bad news from the failure of bank *B*. Excepting the possibility that $R_1 \neq R_0$ in general, this case is the same as the first-investment

problem where the only information was the prior belief. Therefore,

$$r_1^{sf} = u^{-1}(1/\alpha_0) = r_0. \quad (3.15)$$

Observe that while the level of inter-bank correlation c affects the cost of borrowing in the joint survival state, it does not affect the cost of borrowing in the individual survival state. Thus, in this case the payoff to the bank at date 2 from the second period investment, denoted π_2^{sf} , is given by

$$\pi_2^{sf} = \begin{cases} R_1 - r_0 & \text{if } \tilde{R}_1 = R_1 \text{ and } R_1 > r_0 \\ 0 & \text{otherwise} \end{cases}. \quad (3.16)$$

We have assumed here that depositors of the failed bank cannot migrate to the surviving bank. This assumption will be relaxed later and its implications explored fully.

3.5 Information Contagion

We can now characterize the spillover from the failure of a bank on the surviving bank. First, the surviving bank's cost of borrowing rises relative to the state where both banks survive. This is a negative spillover of a bank's failure; or, put another way, the survival of a bank results in a positive spillover on

other surviving banks by lowering the cost of borrowing. In general, this reduces the profits of banks in states where they survive but their peers fail. In particular, if the profitability of the surviving bank's investments is low, the increased borrowing cost also renders the surviving bank unviable: depositors find it better to invest in the storage technology than lend to their bank. In other words, there is a "run" on the surviving bank induced by an updating of the state of the economy by depositors in response to one bank's failure. The result is an "information contagion."⁸

Proposition 5 (Information Contagion) $\forall p, q$, and c ,

$$(i) \ r_1^{ss} < r_1^{sf} = r_0.$$

$$(ii) \ \pi_2^{ss} > \pi_2^{sf}, \forall R_1 > r_1^{ss}.$$

(iii) *Bank A is viable in the joint survival state SS, but is unviable in the individual survival state SF, $\forall R_1 \in (r_1^{ss}, r_0]$.*

Much empirical evidence exists to support such rational updating by depositors and the resulting information spillover on bank values (see Section 3.2). We focus below on a few representative papers.

⁸It is plausible that banks increase their lending rates when faced by an increased borrowing cost. However, this would ration the bank's borrowers with project returns that are lower than the lending rate offered by the bank. Providing that a bank cannot undo completely the decrease in its profits from increased borrowing rates by increasing its lending rates, this result on information contagion holds. We consider this scenario reasonable, given the typical diminishing returns to scale faced by banks on lending side. See ample empirical evidence in the discussion following Proposition 5 that supports the information contagion story.

Slovin, Sushka, and Polonchek (1992) examined share-price reactions to the announcements of seasoned stock issues by commercial banks. They found negative effects (significant -0.6%) on rival commercial and investment banks. In another study, Slovin, Sushka, and Polonchek (1999) investigated 62 dividend reductions and 61 regulatory enforcement action announcements over the period 1975–1992. They found that actions against money center banks had negative contagion-type externality for other money center banks.

In a more direct evidence, Lang and Stulz (1992) investigated the effect of bankruptcy announcements on the equity value of the bankrupt firm's competitors. They found that, on average, bankruptcy announcements decrease the value of a value-weighted portfolio of competitors by 1%. This they attributed to a contagion effect. The effect was stronger for highly leveraged industries (banks being the primary candidate) and for firms exhibiting substantial similarities.

Rajan (1994) looked at the effects of an announcement on December 15, 1989, that Bank of New England was hurt from the poor performance of the real estate sector and that it would boost its reserves to cover bad loans. He found significant negative abnormal returns (-2.4%) for all banks, and the effect was stronger for banks with headquarters in New England (-8%). He also found significant negative abnormal returns for the real estate firms in general, whereas the negative effect is stronger for real estate firms with holdings in New

England. This suggests that the announcement revealed information about the real estate sector and more so about the real estate sector in New England, and that this information was rationally taken into account by investors in their updating process.

In the next section, we explore the consequences of such information contagion for the endogenous choice of inter-bank correlation at date 0. To do so, the following computation of the expected payoff of banks from their second-period investment is required.

3.5.1 Expected Payoff from Second-Period Investment

To calculate the expected payoff to the banks in the second period, we use the superscripts a and b to represent the returns on investments of banks A and B , respectively. Denote $(\tilde{R}_1^a = R_1, \tilde{R}_0^a = R_0, \tilde{R}_0^b = R_0)$ as (R_1, R_0, R_0) and $(\tilde{R}_1^a = R, \tilde{R}_0^a = R_0, \tilde{R}_0^b = 0)$ as $(R_1, R_0, 0)$. We can calculate the ex-ante expected second-period return of bank A (and by symmetry, of bank B) as

$$E(\pi_2(c)) = \Pr(R_1, R_0, R_0) (R_1 - r_1^{ss})^+ + \Pr(R_1, R_0, 0) (R_1 - r_1^{sf})^+$$

where $x^+ = \max(x, 0)$. Furthermore, we obtain

$$\begin{aligned}
\Pr(R_1, R_0, 0) &= \Pr(G) \Pr(R_1, R_0, 0|G) + \Pr(B) \Pr(R_1, R_0, 0|B) \\
&= p(q - c)q + (1 - p)(q - c)(1 - q) \\
&= (q - c) [pq + (1 - p)(1 - q)], \text{ and} \tag{3.17}
\end{aligned}$$

$$\begin{aligned}
\Pr(R_1, R_0, R_0) &= \Pr(G) \Pr(R_1, R_0, R_0|G) + \Pr(B) \Pr(R_1, R_0, R_0|B) \\
&= pcq + (1 - p)(1 - 2q + c)(1 - q). \tag{3.18}
\end{aligned}$$

Substituting these in the expression for $E(\pi_2(c))$, we obtain

$$\begin{aligned}
E(\pi_2(c)) &= [pcq + (1 - p)(1 - 2q + c)(1 - q)] (R_1 - r_1^{ss}(c))^+ + \\
&\quad (q - c) [pq + (1 - p)(1 - q)] (R_1 - r_0)^+. \tag{3.19}
\end{aligned}$$

We assume henceforth that $R_1 > r_1^{ss}(q)$, which ensures that banks are viable in the state SS , $\forall c$. This follows because $r_1^{ss}(c)$ is increasing in c , as shown in Lemma D.1 in Appendix D. That is, the joint survival of highly correlated banks does not convey good news about the overall economy to the degree conveyed by banks' simultaneous survival in a state of lower correlation.

Thus, if $R_1 \in (r_1^{ss}(q), r_0]$, then

$$E(\pi_2(c)) = [pcq + (1 - p)(1 - 2q + c)(1 - q)] (R_1 - r_1^{ss}(c))$$

and if $R_1 \geq r_0$, then

$$E(\pi_2(c)) = [pq^2 + (1-p)(1-q)^2] \cdot [R_1 - (\lambda(c)r_1^{ss}(c) + (1-\lambda(c))r_0)] , \quad (3.20)$$

$$\lambda(c) = \frac{pcq + (1-p)(1-q)(1-2q+c)}{pq^2 + (1-p)(1-q)^2} . \quad (3.21)$$

In particular, if $R_1 \geq r_0$, then expected second-period profits are the expected return on bank loans in the second period minus the expected borrowing cost in the second period. This expected borrowing cost is a weighted average of the costs of borrowing in the states SS and SF , that is, $r_1^{ss}(c)$ and r_0 , with the respective weights being $\lambda(c)$ and $(1-\lambda(c))$. These weights, up to a constant, are simply the probabilities of being in the states SS and SF , respectively. Thus, these expressions make it clear that the level of inter-bank correlation enters the expected return of a bank through the promised interest rates and through the probabilities of joint and individual survival states.

3.6 Choice of Inter-Bank Correlation

In this section, we show that banks choose to be perfectly correlated at date 0 in response to the anticipated information spillover at date 1 when banks fail. If banks survive together, they subsidize each other's borrowing costs. To

capitalize on this, banks prefer to invest in assets correlated with those of other banks by lending, for example, to similar industries or geographic regions.

The objective of each bank is to find the level of inter-bank correlation c that maximizes

$$E(\pi_1) + E(\pi_2(c))$$

where discounting has been ignored since it does not affect any of the results. With first-period profits, $E(\pi_1)$, unaffected by inter-bank correlation, it is the second-period profits, $E(\pi_2(c))$, that determine the preference of banks for correlation.

Consider first the case where $R_1 \in (r_1^{ss}(q), r_0]$. In this case, banks would choose to be perfectly correlated, specifically $c = q$, provided $E(\pi_2(c))$ is increasing in c , $\forall c \in [2q - 1, q)$. This always holds (see the Appendix D). Next, consider the second case where $R_1 \geq r_0$. Again, banks would choose to be perfectly correlated provided $E(\pi_2(c))$ is increasing in c , $\forall c \in [2q - 1, q)$. For the economy studied thus far, this result is always valid as well (see the Appendix D). That is, the expected cost of attracting depositors is minimized when banks are perfectly correlated. The following result on ex-ante herding amongst banks formalizes this intuition.

Proposition 6 (Herding) *The expected second period profits, $E(\pi_2(c))$, in-*

crease in inter-bank correlation c . In equilibrium, banks choose to be perfectly correlated, that is, they choose $c = c_{max} = q$.

The limited liability of banks plays a crucial role here. The information spillover of a bank's failure makes it less attractive for a bank to survive in an environment where the other bank fails than to survive when the other bank also survives. To capitalize on this relative benefit from surviving with the other bank, each bank seeks to increase inter-bank correlation, which increases the likelihood of joint survival (state SS) relative to the likelihood of individual survival (state SF). In so doing, however, the likelihood of joint failure (state FF) also increases relative to the likelihood of individual failure (state FS). Since banks have limited liability in failure, this latter shift in probabilities does not affect bank owners' welfare. Hence, the interaction of limited liability of banks and the information spillover of bank failures leads to ex-ante herding by banks. This intuition is captured well in the expected second-period profits of bank A under different first-period outcomes, as shown in Table 14.⁹

Furthermore, the risk-aversion of depositors plays a crucial role. On the one hand, increasing inter-bank correlation helps banks benefit from more frequent joint survival. However, conditional upon joint survival, the cost of borrowing is $r_1^{ss}(c)$, which is increasing in inter-bank correlation c : survival of both banks

⁹Acharya (2000) refers to such behavior of banks as "systemic risk-shifting," since banks collectively maximize the value of their equity options by holding correlated portfolios.

is not as good news about state of the economy if banks are more correlated as when they are less correlated. Formally, relative bank profits between joint survival and individual survival states, $[\pi_2^{ss}(c) - \pi_2^{sf}]$, are a decreasing function of c , because π_2^{sf} is independent of c . At first blush, this might suggest that banks would resist choosing the highest possible level of inter-bank correlation. The proof in the Appendix D, however, shows that as long as depositors are risk-averse, i.e., $u''(\cdot) < 0$, the decrease in relative profits $[\pi_2^{ss}(c) - \pi_2^{sf}]$ as c increases is more than offset by the corresponding increase in the relative likelihood of joint survival state. Hence, herding takes the extreme form of $c = c_{max}$ whenever depositors are risk-averse.

Formally, expected bank profits are equal to expected loan returns minus the weighted average cost of borrowing in states SS and SF , the weights being the probabilities of these states, respectively. With risk-neutrality, any weighted average of $r_1^{sf}(= r_0)$ and $r_1^{ss}(c)$ equals $r_1^{ss}(c_{max})$ for all possible c . Hence, banks remain indifferent between alternate choices of inter-bank correlation.¹⁰ With risk-averse depositors, banks pay an extra premium for the risk-aversion of the depositors. The gap between the interest paid in states SF and SS , that is, $[r_0 - r_1^{ss}(c)]$, widens as the probability of the high return is reduced. As a result, when depositors are risk-averse, r_0 is large enough

¹⁰Thus, if depositors are risk-neutral, it is straightforward to show that the choice of inter-bank correlation is, in fact, indeterminate.

compared to $r_1^{ss}(c)$ so that any convex combination of r_0 and $r_1^{ss}(c)$ is larger than $r_1^{ss}(c_{max})$, for all c . In turn, banks prefer the highest level of inter-bank correlation c_{max} , since that produces the lowest cost of borrowing.¹¹

Under our assumed two-point return distribution for each bank, the information spillover arises precisely when a bank fails. We might, however, consider the implications of assuming a continuous return distribution. In this case, the information event that leads depositors to update their beliefs about the state of the economy need not only be bank failures. In fact, any combination of realizations of bank profits leads to rational updating by depositors. The overall spillover nevertheless remains qualitatively similar. The bank with superior performance always suffers some information spillover due to the relatively inferior performance of the other bank. To summarize, date 1 in our model could be considered simply an “information event” that leads to rational updating by depositors. The resulting revision of borrowing costs would affect bank profits as long as banks require additional financing.

In the next section, we show that if depositors of the failed bank choose rationally between lending to the surviving bank and investing in risk-free technology, then banks do not always choose to be perfectly correlated. That is, herding incentives are mitigated.

¹¹This result holds even if we assume a more general form $f(c)$ for the effect of inter-bank correlation c on the joint distribution of bank returns, as discussed in footnote 6.

3.6.1 Flight to Quality

We relax the assumption that depositors of the failed bank simply keep their goods in storage. Suppose in state SF , the depositors of the failed bank migrate to the surviving bank. Clearly, such a migration is individually rational for depositors only if the surviving bank is viable, that is, if it has profitable opportunities whose returns exceed the promised deposit rate in some states of the world. We call such migration “flight to quality” since depositors migrate from a failed bank that had a poor realization of loan returns to a surviving bank that had better quality of loan performance (and that is also expected to be viable in future). The effect of such flight to quality is essentially to increase the scale of the surviving bank: the surviving bank receives total deposits of two units when it is the only surviving bank, rather than its previous allocation of one unit. This increases the attractiveness of state SF compared to the situation without flight to quality. In turn, it mitigates the herding behavior of banks.

In the presence of flight to quality, the expected second-period profits of

banks, denoted as $E(\pi_2^{FQ})$, are given as:

$$\begin{aligned}
E(\pi_2^{FQ}(c)) &= [pcq + (1-p)(1-2q+c)(1-q)](R_1 - r_1^{ss}(c))^+ + \\
&\quad 2(q-c)[pq + (1-p)(1-q)](R_1 - r_0)^+ \\
&= E(\pi_2) + [(q-c)(pq + (1-p)(1-q))](R_1 - r_0)^+. \quad (3.22)
\end{aligned}$$

The expected profits in the absence of depositor migration are augmented by the increase in scale of the surviving bank, provided depositors migrate, that is, if $R_1 > r_0$.

To examine the choice of inter-bank correlation, we consider the behavior of $E(\pi_2^{FQ}(c))$ as a function of c . It follows that

$$\frac{\partial E(\pi_2^{FQ})}{\partial c} = \frac{\partial E(\pi_2)}{\partial c} - (pq + (1-p)(1-q))(R_1 - r_0)^+. \quad (3.2)$$

The first term on the right hand side of the above equation is positive, as shown in Proposition 6, and induces banks to correlate with other banks. However, the prospect of increased profits conferred by survival in an environment of failure of the other bank induces a countervailing incentive. The effect of flight to quality is thus to weaken the herding incentives. In fact, if the attractiveness of second-period investments, measured by R_1 , is sufficiently high, then increasing the scale of the bank dominates any induced spillover. Thus,

banks choose to be minimally correlated at date 0. For intermediate values of R_1 , banks choose an interior level of correlation, which is decreasing in the profitability of the second-period investment, R_1 .¹²

Proposition 7 (Flight to Quality and Pro-Cyclical of Herding) *In the*

presence of flight to quality, $\forall p$ and q , $\exists R_1^* > r_0$ and $\exists R_1^{**} \geq R_1^*$ such that

(i) $\forall R_1 \in (r_1^{ss}(q), R_1^*)$, banks choose to be perfectly correlated, that is, they choose $c = c_{max} = q$;

(ii) $\forall R_1 \in [R_1^*, R_1^{**})$, banks choose an interior level of correlation $c^*(R_1) \in (c_{min}, c_{max}) = (2q - 1, q)$ such that $c^*(R_1)$ is decreasing in R_1 ; and

(iii) $\forall R_1 \geq R_1^{**}$, banks choose the lowest level of correlation, that is, they choose $c = c_{min} = 2q - 1$.

There exist parameter values for which $R_1^{**} = R_1^*$, so that the choice of inter-bank correlation switches directly from c_{max} to c_{min} as R_1 increases. The numerical examples, available upon request from the authors, show, however, that there also exist robust sets of parameterizations such that $R_1^{**} > R_1^*$. The result is a choice by banks for an interior level of correlation over the range $R_1 \in [R_1^*, R_1^{**})$.

¹²If each bank chooses from one of two possible industries to lend to, then Proposition 7 would imply that there is a critical value of R_1 , the future profitability of loans, such that below this critical value, banks choose to lend to the same industry, and above this critical value, banks choose to lend to different industries.

Empirical evidence supports the migration of survivors of failed banks to surviving banks, while also indicating that when information contagion is sufficiently severe investors flee the banking sector as a whole, taking their deposits with them.

Saunders and Wilson (1996), for example, examined deposit flows in 163 failed and 229 surviving banks over the Depression era of 1929–1933 in the U.S. They found evidence for flight to quality for years 1929 and 1933: withdrawals from the failed banks during these years were associated with deposit increases in surviving banks. However, for the period 1930–1932, deposits in failed banks as well as surviving banks decreased, which the authors interpreted as evidence for contagion. Importantly, the deposit decrease in the failed banks exceeded those at the surviving banks, most likely a manifestation of rational updating of beliefs about bank prospects by informed depositors. In another study, Saunders (1987) studied the effects on the other banks' deposits due to two announcements regarding an individual bank in April and May 1984. While the first announcement did not have a significant effect, the second one, made by the U.S. Office of the Comptroller of the Currency, resulted in a flight to quality.

Numerical examples, available upon request from the authors, illustrate that herding is stronger (in terms of the range of future profitability of loans over which banks choose high inter-bank correlation) when the likelihood of

bad state of the economy is high (p low) and when the systematic risk of loans is high (q high). More broadly, we interpret the result in Proposition 7 as the “procyclicality” of herding.

Pro-cyclicality of herding: Historical evidence that relates to bank lending and its fluctuations suggests that herding is pro-cyclical. That is, lending surges to some industry in the economy at peaks in the cycle affecting that industry, and a sharp contraction ensues at troughs of the cycle.

The present analysis provides a possible rationale for such pro-cyclical lending behavior. At business cycle peaks, the expected future return on bank investments is lower (lower R_1), for example, due to a possible slow-down in the economy. Thus, the expected benefit to banks in differentiating from other banks is not large. Simply stated, there is not much business for banks in the forthcoming periods. Such an economic state causes herding incentives to dominate and banks to continue to lend to a common industry. By contrast, at business-cycle troughs, the future profits from bank investments are attractive (higher R_1). The consequent expected benefit of survival when other banks fail, for example, through an increase in the scale of business, are sufficient to overcome the benefits of herding. The result is that banks differentiate at the troughs and lending to a common industry is retrenched.

Furthermore, if returns on bank investments indeed exhibit such cyclical

behavior, then aggregate bank lending to a particular industry must show a “trend-chasing” behavior. Indeed, Mei and Saunders (1997) demonstrated that investments in real-estate by U.S. financial institutions tended to be greater precisely in those times when the real-estate sector looked less attractive from an ex-ante standpoint. Interpreting such behavior at the level of an individual bank or institution may perhaps suggest a behavioral inefficiency on part of the loan officers: banks appear to increase their lending to an industry when its expected returns are falling and reduce their lending when its expected returns are rising. However, when viewed in the context of the herding incentives of banks, this is exactly the lending behavior one should anticipate from profit-maximizing loan officers.

In fact, the findings of Mei and Saunders provide a possible means to distinguish our results from those of herding models that are based on considerations of managerial reputation. We discuss two of these models, Scharfstein and Stein (1990) and Rajan (1994), in some detail in the next section. Scharfstein and Stein’s sequential model of herding is quiet about the variation in herding behavior over the business cycle. Rajan’s simultaneous herding model more closely resembles the model of the present paper. In Rajan’s model, banks coordinate and hide their losses in business cycle peaks when public information about the poor performance of the corporate sector has not become available. This leads to excessive lending in these periods. However, in business cycle

troughs when the corporate sector performance is public knowledge, banks announce their losses and take profit-maximizing lending decisions. This latter result contradicts the finding of Mei and Saunders that banks act in a trend-chasing behavior in both business cycle peaks and troughs. By contrast, our model is able to explain this evidence consistently in peaks as well as troughs.

3.6.2 Relationship to Herding Linked to Managerial Reputation

Scharfstein and Stein (1990), Rajan (1994) modeled herding behavior based on managerial concerns for reputation.¹³ Scharfstein and Stein's model involves sequential herding in investments. Rajan's model involves simultaneous herding by bank managers as they announce losses on their loan portfolios and adjust their credit policies when faced with short-term horizons.¹⁴ In these models, it is privately optimal for managers to fail when other managers fail so as to "share the blame." This leads to a preference for correlated investments or correlated announcements of losses. By contrast, in our model, it is privately optimal for bank owners to succeed when other managers succeed

¹³Other incentives for managerial herding ("conservatism") have also been discussed in the literature. See, for example, Zwiebel (1995) and the survey article by Devenow and Welch (1996).

¹⁴Rajan (1994) also provides evidence for his theory based on the New England Banking Crisis of 1990. He shows that the banks "bunch" their provisioning and charge-off decisions: the quarterly bank loan loss provisions (charge-offs) in New England are significantly related to the quarterly loan loss provisions (charge-offs) of other banks in New England.

since each bank's success subsidizes the other banks' borrowing costs. Hence, the channel of information contagion in our paper is complementary to that of Scharfstein and Stein, and Rajan.

In fact, the findings of Mei and Saunders (1997) provide a possible means to distinguish our results from those of herding models that are based on considerations of managerial reputation. Scharfstein and Stein's sequential model of herding is quiet about the variation in herding behavior over the business cycle. Rajan's simultaneous herding model more closely resembles the model of the present paper. In Rajan's model, banks coordinate and hide their losses in business cycle peaks when public information about the poor performance of the corporate sector has not become available. This leads to excessive lending in these periods. In spirit, this is similar to herding in our paper where banks attempt to reveal less adverse information about the common factors affecting loan returns by choosing assets that are more correlated with other banks. However, during business cycle troughs in Rajan's model when the corporate sector performance is public knowledge, banks announce their losses and take profit-maximizing lending decisions. This latter result contradicts the finding of Mei and Saunders that banks act in a trend-chasing behavior in both business cycle peaks and troughs. By contrast, our model is able to explain this evidence consistently in peaks as well as troughs.

Furthermore, these papers discuss the managerial concern for profits as a

countervailing force to herding behavior. For example, Rajan (1994) adds profits to the objective function of managers and demonstrates its countervailing effect over a set of parameters. According to this theory, bank herding should decrease in the extent of managerial (or central loan officers') alignment with bank profits, proxied say by their incentive compensation. In our paper, managers of limited liability banks maximize bank profits, and yet there is herding. Aligning managerial objectives with maximization of bank profits may thus not be sufficient to ameliorate herding behavior. Put even more strongly, maximization of profits may not be a countervailing force to herding behavior at all. Managerial reputation and profit maximization can both generate herding, which as a result may be a robust economic outcome, even under settings where managerial discretion over timing of charge-offs is restricted. While we are not aware of a test linking herding behavior to incentive compensation, our theory in contrast to Rajan's, would predict that bank herding in fact increases in the extent of managerial alignment with bank profits.

Another relevant factor in the managerial herding theory is the reward to managers for relative ability, that is, the reward for being successful when others fail. These papers do not model such relative rewards, but instead argue that they counteract herding incentives. Such relative rewards correspond closely to the flight to quality aspect in our model which generates the procyclical herding pattern.

Finally, in Scharfstein and Stein (1990) and Rajan (1994), the distribution of outcomes is assumed to be asymmetric over states. This is the main factor driving the herding results in these papers. To summarize their distribution assumptions, there is only one way for managers to be correct, but several different ways for them to be incorrect. By contrast, we assume a symmetric distribution for joint success and failure. In our model, asymmetry arises in the payoffs of bank owners due to the interaction of limited liability and information contagion. Furthermore, in the presence of flight to quality, allowing an asymmetric distribution of outcomes in our model strengthens the herding incentives as we now demonstrate.

Thus far, the probability of high return (R_t) in the good state (G) and the probability of low return (0) in the bad state (B) were both assumed to be equal to q . Suppose we allow for different values of q in each state. For example, suppose that

$$\Pr(R_t|G) = q_1 \quad \text{and} \quad \Pr(0|B) = q_2, \quad q_2 > q_1. \quad (3.23)$$

This means that outcomes are more correlated with the state of economy when it is the *Bad* state: low outcome in the *Bad* state is more likely than high outcome in the *Good* state. In this case, when one bank survives but the other bank failed (state SF or FS), the posterior probability of the high state

is lower than the prior of p . Formally,

$$\Pr(G|SF) = \frac{p(q_1 - c)}{p(q_1 - c) + (1 - p)(q_2 - c)} < p.$$

Therefore, r_1^{sf} exceeds r_0 whereas they were equal in the model thus far. In turn, even if all depositors fly to the surviving bank, the bank has to pay a higher rate and the benefit from flight to quality is reduced. In the extreme case, r_1^{sf} exceeds R_1 and all funds escape the banking system. Ex-ante, this strengthens the herding incentives of banks.

3.6.3 Extensions

Effect of Heterogeneity and More Than Two Banks: We extend the basic model to derive conclusions regarding properties of banks for which information contagion, and by implication the herding incentives, are likely to be stronger. For simplicity, we do not state our results in this section as formal propositions.

Suppose there are three banks in the model, but one of the banks is a “foreign” bank. The foreign bank also has access to a set of depositors with a unit of consumption good each period. The foreign bank is affected by a foreign systematic risk factor, whereas the two “domestic” banks are affected by the same domestic systematic risk factor. Suppose that the probabilities

of the good state and the high return are the same as before for each bank. That is, the probabilities have the same value ex-ante for all banks, the return realizations are drawn from the same distribution for the two domestic banks, but they are drawn from a different distribution for the foreign bank.

Under this structure, the realization of domestic banks' returns conveys no information about the foreign systematic risk factor, and vice versa. The updating by depositors and the promised rates are thus the same for the two domestic banks and identical to the values derived in the analysis thus far. However, this is not the case for the foreign bank. Suppose that the foreign bank had the high return in the first period. Then, denoting G^f and B^f as the *Good* and the *Bad* states for the foreign systematic risk factor, we obtain

$$\Pr(G^f|R_0) = \frac{pq}{pq + (1-p)(1-q)} , \quad (3.24)$$

$$\Pr(B^f|R_0) = \frac{(1-p)(1-q)}{pq + (1-p)(1-q)} . \quad (3.25)$$

Using these, the probability of a high return for the foreign bank in the second period, given the foreign bank had a high return in the first period, is calculated as

$$\begin{aligned} \alpha_1^f &= \Pr(R_1|R_0) = \frac{pq}{pq + (1-p)(1-q)} q + \frac{(1-p)(1-q)}{pq + (1-p)(1-q)} (1-q) \\ &= \frac{pq^2 + (1-p)(1-q)^2}{pq + (1-p)(1-q)} . \end{aligned} \quad (3.26)$$

The promised return to the foreign bank's depositors at date 1, r_1^f , thus satisfies

$$\alpha_1^f u(r_1^f) = 1.$$

Since $\alpha_1^f = \alpha_1(c_{\max}) > \alpha_0$, it follows that $r_1^f = u^{-1}(1/\alpha_1^f) < r_0$. Therefore, when one of the domestic banks fails, the foreign bank (if it has survived) can attract depositors by offering a lower promised rate than the surviving domestic bank.

More generally, suppose that due to geographic segmentation and/or due to diseconomies of scope, one set of banks is different from the other set in terms of loan portfolio exposure. Then, upon the failure of some banks, deposits would rationally “fly” to banks that are considered different from, and hence deemed safer than, the failed banks. As a result, the banks considered to be similar to the failed ones will observe a decrease in their deposit base even though they have not failed. Calling this phenomenon as “flight to quality” is even more appropriate than before since depositors migrate to a set of banks deemed safer than the banks they had lent to earlier. To summarize, the benefit from flight to quality to dissimilar banks could result in the accentuation of information contagion for similar banks.

Consistent with this, Kaufman's (1994) survey on systemic risk documented abnormal negative returns of other banks when a given bank fails, only if

the surviving banks also invested in the same product or market area. In another piece of supporting evidence, Schumacher (2000) examined the 1995 banking crisis in Argentina triggered by the 1994 Mexican devaluation. Her analysis showed evidence of bank-specific contagion and flight to quality, rather than a contagion to the whole system. More specifically, after the failure of some domestic wholesale banks, surviving domestic wholesale banks suffered significant deposit losses. The suspension of retail bank operations increased the withdrawals from surviving small retail banks. But the foreign retail banks, and to some extent large domestic banks, had significant increases in their deposits during the crisis.

Consider next the failure of the foreign bank. Since the foreign bank's loan returns are affected by a systematic factor that is different from the one affecting domestic banks' loans, it follows that its failure has no impact on the cost of borrowing for the domestic banks. We conclude that information contagion is more likely to arise from the failure of banks whose portfolio returns are anticipated to be more correlated with the overall state of economy. Furthermore, the information contagion is likely to be localized, affecting those banks the most whose portfolio returns are also anticipated to be highly correlated with the overall economy. Banks affected largely by factors that are not related to factors affecting the failed banks may in fact benefit due to migration of depositors. By implication, herding amongst banks should be a localized

phenomenon as well.

Competitive Effect on Loan Rates: The flight to quality phenomenon can be interpreted as a mechanism of competition amongst banks. Thus far we assumed that loans made by banks are to their “captive” borrowers so that the effect of competition for loans could be suppressed. Direct competition for loans to “non-captive” borrowers would suggest that if banks correlate their investment portfolios, for example by lending to firms in the same industry, then they reduce each other’s profit margins. Lang and Stulz (1992) found that the competitors of failed firms benefitted from the failed firms’ bankruptcies for industries with high concentration and low leverage. This is another possible explanation for the finding of Slovin, Sushka, and Polonchek (1999) that regulatory actions against money center banks (MCBs) in the U.S. had negative contagion-type effects for other MCBs, whereas the actions against regional banks had positive competitive effects on geographic rivals.

A fully structural analysis of this effect is beyond the scope of this paper. Nevertheless, the likely effect can be well understood by positing a reduced-form return on bank loans as a decreasing function of inter-bank correlation. Let $R_0(c) = R_1(c) = (R - \delta c)$. Assume for simplicity that there is no flight to quality. It can be shown that in this case herding incentives are weakened. Formally, the choice of inter-bank correlation is given by a function $c^*(\delta)$ which

is decreasing in δ : the greater the competition in lending markets, the lower is the propensity of banks to lend to similar industries.

Inter-Bank Linkages: Rochet and Tirole (1996), Allen and Gale (2000), and Dasgupta (2000), to cite a few, consider contagion arising from inter-bank linkages such as inter-bank deposits that provide liquidity insurance to banks. Such linkages do not affect the main thrust of our herding results. If inter-bank deposits are priced fairly in each state of the world, then their usage does not affect expected profits for the lender bank. However, the borrower bank's profits increase as it can potentially avoid default by drawing down inter-bank deposits when its loan returns are insufficient to meet deposit payments. This reduces the information spillover and mitigates herding incentives. However, for the borrower bank to be able to pay back the lender bank as well as the depositors, the second period return (R_1) has to be sufficiently high. Otherwise, either the lender bank or the depositors (depending on the seniority) would not lend.

If the provision of liquidity insurance is mutual and entails no ex-ante cost but only an ex-post cost to banks, then the (ex-post) lender bank faces an additional withdrawal when the (ex-post) borrower bank accesses the insurance. In the context of our model, bank A 's profits in state FS are not zero as it can access liquidity insurance from bank B and possibly avoid failure. In state

SF , however, bank A 's profits are reduced as bank B uses insurance provided by bank A . The exact mitigation of herding incentives depends upon the net transfer of profits of bank A between states SF and FS , but does not affect their qualitative nature.

More generally, we consider the information channel of contagion to be an important, complementary channel to the one of inter-bank linkages. In fact, empirical evidence has found it hard to attribute the magnitude of contagion effects purely to inter-bank linkages. Kaufman (1994) claims that there is little direct evidence to suggest that inter-bank exposure has served to transmit shocks from failing banks to solvent banks. He presents the case of Continental Illinois Bank, the seventh largest bank in the U.S. when it failed in 1984, as providing evidence against a significant role being played by inter-bank linkages in contagion.¹⁵

¹⁵Shortly before its failure, 2299 banks had exposure to Continental Illinois in terms of deposits or funds (U.S. Congress, 1984). 976 of these banks had exposures more than the government insured amount of \$100000, only 65 banks had uninsured exposures in excess of 100% of their capital, while 101 banks had uninsured exposures of between 50% and 100% of their capital. Kaufman (1985, 1994) estimate that if the losses in Continental Illinois bankruptcy were as large as 60 cents on the dollar, then only 27 of the 2299 banks would have suffered uninsured losses in excess of their capital and become legally insolvent, these losses amounting to a total of \$137 million. Another 56 banks would have suffered losses between 50% and 100% of their capital and these losses would have totaled \$237 million. If the losses in Continental were 10 cents on the dollar, then no banks would have suffered losses more than their capital, while only 2 banks would have suffered losses more than 50% of their capital with these losses amounting in total to only \$1 million. The actual losses in Continental were less than 5 cents on the dollar and as estimated by the mentioned studies, no correspondent bank experienced threatening losses.

3.7 Efficiency Analysis

Two matters point to the undesirability of herding by banks. One concerns the fact that when banks herd, they may ignore the profitability of firms and industries they can lend to. This effect is similar to that considered in the reputation-based herding models of Scharfstein and Stein (1990), Rajan (1994). To embed the inefficiency that arises from this effect, we revert to the two-bank case but relax the model to permit the possibility of differential returns to banks from the firms and industries to which they can lend.

The loss in diversification faced by investors constitutes the second reason why herding by banks can be socially undesirable. Depositors or public equity holders hold less diversified portfolios when banks herd, provided these investors have access to multiple banks. This effect generates excessive aggregate risk in the economy and leads to welfare costs that are different from those described above. A complete analysis embedding such welfare costs requires additional machinery and is beyond the scope of the current paper. In our model, depositors lend to only one bank, and there are no public equity holders. Hence, we focus on the welfare costs that arise from the passing up of profitable projects by banks.

We perform a somewhat restricted efficiency analysis in the sense that bank borrowers are “captive” whereby all economic rents from the borrowing firms’

technologies are captured by their respective banks. Suppose there are two possible industries in which banks can invest, denoted 1 and 2. Bank A (B) can lend to firms A_1 and A_2 (B_1 and B_2) in industries 1 and 2, respectively. We assume for simplicity that all firms are equally profitable in the first period, i.e., they have identical return R_0 in high state in the first period. However, firms may have different levels of profitability in the second period. Bank owners receive signals at date 0 about the profitability of *all* firms in the second period. In particular, they receive a signal whether the return on a firm in the high state in the second period is R_1 or $(R_1 + \epsilon)$, $\epsilon > 0$. One of the two firms available to each bank has a return of R_1 , whereas the other firm has a return of $(R_1 + \epsilon)$. After receiving these signals, bank owners decide which firm to lend to.¹⁶ For simplicity, the signals are perfect: bank owners know the true return on each firm with certainty. A coordination game results if banks are assumed to play a Nash strategy in their choice of industry. The outcome of this game determines the inter-bank correlation.

If banks choose to lend to firms in the same industry, specifically they either

¹⁶Implicitly, we assume here that if banks lend to a firm in the first period, they continue to lend to the same firm in the second period. It is straightforward to relax this assumption and allow banks to receive private signals about $\tilde{R}_0$, the first-period profitability of firms. Furthermore, if we allow banks to receive signals only about the firms they can lend to and not about firms that other banks can lend to, then the analysis is more involved. With private signals, bank actions potentially reveal their information to other banks. We wish to consider a coordination game between banks and hence assume that each bank knows profitability of all firms in the economy even though this is unfortunately in conflict with the earlier assumption that bank borrowers are “captive” to their respective banks.

lend to A_1 and B_1 , or they lend to A_2 and B_2 , then they are perfectly correlated ($c = q$). However, if they choose different sectors, then their returns are imperfectly correlated, say independent ($c = q^2$). With only a few additional assumptions, this two-industry structure maps onto our model that permits choice of inter-bank correlation, but limits that choice to two values, $c = q$ or $c = q^2$. These assumptions are as follows: First, bank owners make their lending decisions simultaneously. Second, we assume that $R_1 > r_0$, so that bank A (B) is viable in the state SS as well as in the states SF (FS). Finally, there is no flight to quality upon bank failures at date 1. The implications of relaxing these assumptions are discussed later.

By symmetry, it suffices to analyze the two possible information structures that arise as shown in Tables 15 and 16. In structure (A_1, B_1) , firms A_1 and B_1 have the higher return ($R_1 + \epsilon$). In structure (A_1, B_2) , firms A_1 and B_2 have the higher return. We wish to compare bank lending decisions under these information structures to the *first-best* investments and to the *constrained efficient* investments. Under the first-best investments, financial intermediation is not required: funds in the economy can be directly lent to firms in different industries and transfers made across economic agents. In particular, funds are lent to the most profitable firms available. By contrast, under constrained efficient investments, a financial intermediation structure that includes the deposit contract, is taken as given. Constrained efficient investment choices maximize

the total expected profits of banks in the economy, because depositors in our economy are always guaranteed a fixed reservation utility in both periods.

From Table 15, it follows that the first-best investments under the information structure (A_1, B_1) involve lending funds of depositors of bank A to firm A_1 and funds of depositors of bank B to firm B_1 . Similarly, the first-best investments under the information structure (A_1, B_2) involve lending to firms A_1 and B_2 .

The following proposition establishes that bank investments are in general not first-best efficient. Under the information structure (A_1, B_2) , bank investments are in general not first-best efficient. The first-best requires banks to invest in different industries in this case, but banks herd and lend to firms in the same industry as long as the differential return between the more profitable firms of the two industries is not too large. The intuition is that if the benefits of differentiating from other banks is not large enough, then banks herd to reduce expected losses tomorrow from information spillovers. Consequently, inter-bank correlation is greater than the one under efficient investments and thus generates excessive systemic risk. For the same reason, under information structure (A_1, B_1) , if the differential return is not high enough, there exist two equilibria one of which is first-best efficient and Pareto dominates the other.

Proposition 8 (Herding and First-Best Investments) *Assume there is*

no flight to quality upon bank failures at date 1. $\exists \epsilon^*$, a critical level of differential return between the firms, such that

(i) Under the information structure (A_1, B_1) ,

(a) if $\epsilon < \epsilon^*$, then two Nash equilibria exist: Bank A lends to firm A_1 (A_2) and bank B lends to firm B_1 (B_2). The equilibrium where bank A lends to firm A_1 and bank B lends to firm B_1 is the Pareto-dominating equilibrium and gives rise to first-best investments.¹⁷

(b) if $\epsilon \geq \epsilon^*$, bank A lends to firm A_1 and bank B lends to firm B_1 in the unique Nash equilibrium giving rise to first-best investments.

(ii) Under the information structure (A_1, B_2) ,

(a) if $\epsilon < \epsilon^*$, then two Nash equilibria exist that are not Pareto-ranked and neither of which lead to first-best efficient investments: bank A lends to firm A_1 (A_2) and bank B lends to firm B_1 (B_2), whereas the first-best investment leads to lending to firms A_1 and B_2 .

(b) if $\epsilon \geq \epsilon^*$, bank A lends to firm A_1 and bank B lends to firm B_2 in the unique Nash equilibrium giving rise to first-best investments.

Thus, passing up of superior investments in favor of investments correlated with other banks gives rise to inefficiency of herding relative to the first-best. With the possibility of flight to quality at date 1, the nature of inefficiency

¹⁷ We focus our analysis on pure strategy equilibria. There does exist a mixed-strategy equilibrium but it is also Pareto-dominated.

under the information structure (A_1, B_2) remains qualitatively similar. Formally, herding leads to inefficient investments under the information structure (A_1, B_2) if and only if $\epsilon < \epsilon^{**}$, where $\epsilon^{**} < \epsilon^*$. Interestingly however, flight to quality may itself generate inefficient investments. Consider the information structure (A_1, B_1) . In this case, the first-best investments involve lending all goods to industry 1. However, the prospect of capturing profits at date 1 through flight to quality gives incentives to banks to differentiate by lending to less profitable industries. This incentive prevails if both industries are sufficiently profitable, that is, R_1 is sufficiently high (as in Proposition 7), but industry 1 is not too profitable compared to industry 2, that is, ϵ is sufficiently small.

A formal statement of the efficiency properties with flight to quality is rather messy, since different equilibria arise depending upon the magnitudes of R_1 and ϵ . We simply summarize it with the following observation. To conclude that flight to quality and competitive effects akin to it are a panacea that always mitigate the inefficiency of investments under herding is not correct in general. First-best investments may require banks to lend to the same industry if that industry is highly profitable compared to other industries. Flight to quality however provides incentives to differentiate even in these cases.

First-best investments may however be too strict an efficiency criterion. If the planner must take the nature of intermediation, in particular the separation

of bank owners and depositors, as given, then the information spillover is in fact ex-post efficient from the planner's standpoint as well. When the planner is thus constrained, we obtain the following result in our model. Investment choices made by banks are the same as those of the constrained planner.

Proposition 9 (Herding and Constrained Efficiency) *Lending decisions of banks and the resulting inter-bank correlation are constrained efficient under the information structures (A_1, B_1) and (A_1, B_2) .*

The intuition is as follows. Promised interest rates in our model guarantee depositors their reservation utility in both periods. Hence, the constrained planner makes lending decisions that maximize the welfare of banks. Since bank owners are risk-neutral, their welfare is identical to their expected profits. Due to symmetry, this in turn is exactly identical to the objective of each set of bank owners and gives rise to the constrained efficiency of their investments. Importantly, this result holds even if (i) we allow for flight to quality upon bank failures at date 1, and (ii) we relax the assumption that $R_1 > r_0$ whereby information contagion can render an otherwise viable bank unviable (Proposition 5). Flight to quality leads to benefits for banks in the second period. If $R_1 < r_0$, then the costs of information spillover are greater. If banks herd, they reduce the impact of the spillover but give up second-period profits to be made from flight to quality. The equilibrium lending decisions of

banks trade off these two effects in precisely the same manner as would the constrained planner.

This is an interesting result in itself since it is in contrast to the inefficiency that arises in other herding models. In the context of our model, banks fully internalize the costs of information contagion and minimize these costs by herding. Systemic risk arising from such herding is thus socially (constrained) efficient. An important implication of this result is that the presence of herding and the attendant increase in the joint bank failure risk are not sufficient to warrant a regulatory intervention.

We do not imply though that herding will always be constrained efficient. Instead, we interpret the result as suggesting that bank herding in response to the information contagion constitutes an inefficiency only if herding and/or contagion lead to costs over and above the costs to bank owners, for example, due to herding arising from managerial reputation considerations as in Scharfstein and Stein (1990) and Rajan (1994). One conclusion relevant for policy debate is that, given the costs of ex-post contagion to bank owners, it is difficult to isolate the extent of ex-ante herding that is socially inefficient. More empirical research aimed at identifying socially efficient levels of bank lending to different industries, and in turn at determining the socially inefficient levels of bank herding, is called for. A welfare analysis that takes into account the micro-motives for existence of banks may suggest the nature of the

additional costs of herding and contagion beyond those to bank owners. Such costs arise for example in models that incorporate the effects of bank failures on the real sector (Bernanke, 1983), the effect of bank failures on the risk-free rates of interest in the economy (Acharya, 2000), and the liquidity provision role of banks on both the asset and liability sides (Diamond and Rajan, 2001a, 2001b).¹⁸

3.8 Bank Regulation and Policy Implications

Our model abstracted from issues concerning bank regulation. This is justified in our setting since we obtain constrained efficiency of bank decisions. Also, the results we derived are potentially relevant for unregulated industries. Nevertheless, taking bank regulation as given, we consider its implications for our results.

3.8.1 Deposit Insurance

Most banking systems have deposit insurance. Full deposit insurance renders deposit rates insensitive to fluctuations in bank's health and reduces informa-

¹⁸The recent work of Diamond and Rajan (2001a, 2001b) suggests that modeling the liquidity provision role of banks on both the asset and liability sides leads to interesting interactions of bank solvency and bank liquidity at both the individual bank level and in the aggregate. Incorporating ex-ante portfolio choices in such micro-models appears to be a fruitful goal that to the best of our knowledge has not yet been pursued.

tion contagion of the sort we described. However, the provision of deposit insurance is only partial in most countries. Furthermore, banks also have subordinated debt in their capital structures that is typically not insured and is often the marginal source of funds. Interest rates on both uninsured deposits and subordinated debt should respond to information pertaining to the bank's health. Thus, in a world with deposit insurance, information contagion would still arise, but its effect on bank profits would be restricted to the amount of uninsured and subordinated debt.

To this extent, deposit insurance only partially mitigates ex-post information contagion and in turn ex-ante herding. While this role of deposit insurance as a provision for confidence in the banking system has been well recognized, its effect on herding has not been documented before. Any welfare analysis of deposit insurance must also account for an implicit cost: the lack of incentives for insured depositors to differentiate between sound and unsound banks reduces the competitive (flight to quality) benefits to banks.

3.8.2 Bank Bailouts

When information contagion is severe in our model, banks that would survive when other banks survive are rendered unviable when these other banks fail. In the absence of flight to quality, such failures can lead to welfare losses. Bank bailouts in this situation mitigate the ex-post costs of information contagion for

these banks and the economy at large. Hence, they also mitigate bank incentives to herd ex-ante. Such forbearance is, however, typically time-inconsistent, as studied by Mailath and Mester (1994): exercised forbearance levels exceed the optimal ex-ante level. Furthermore, in models where regulators are captured by the interests of bank owners, discretion over such forbearance leads to a “too-many-to-fail” guarantee where banks rationally anticipate a greater likelihood of failure if they fail together. This in turn generates a collective moral hazard that gives rise to herding incentives, as demonstrated in Acharya (2000).

3.8.3 Bank Capital

Consider first the private choice of bank capital. Capital buffers a bank from failure by lowering the critical return on loans below which the bank defaults (as would be the case in a richer model with continuous returns on bank loans). Hence, banks can employ capital as a strategic device to reduce the ex-post impact of information contagion from other banks. Note that herding is also a strategic device that serves a similar purpose. While issuance of capital may entail dilution costs to bank owners, as in the models of Gorton and Winton (1999), Bolton and Freixas (2000), herding entails costs to bank owners as well due to passing up of profitable investments. The role of bank capital as a substitute to herding is thus quite sensitive to the relative magnitude of these

costs.

The extent of information contagion is linked to the extent of systematic and idiosyncratic risks of bank loans. Thus, the levels of bank capital should vary cross-sectionally and in time-series as a function of these components of bank portfolio risk. To our knowledge, this empirical issue has not been investigated in detail. Hoggarth and Pain (2002) however do document that bank provisioning against expected losses in the UK is positively linked to the industry concentration of aggregate bank lending. Finally, if dilution costs of capital issuance were mere transfers in the economy, then capital issuance might be less costly from a social standpoint than from the bank owners' standpoint. This should give rise to a role for minimum capital requirements as a device to pre-commit banks to reduce herding.

3.9 Conclusion

We have undertaken an ex-ante analysis of systemic risk amongst banks. Information contagion generates costs for banks that mitigate its impact on their profits by herding. While most studies of systemic risk and financial fragility are concerned with the ex-post effects of bank failures, our paper demonstrates that analyzing the ex-ante response of banks to these effects is important. The extent of herding, the ex-ante aspect of systemic risk, affects the likelihood of

joint failure of banks, but also affects and is affected by the extent of information contagion, which is the ex-post aspect of systemic risk.

An important implication of our paper is the pro-cyclical nature of herding amongst banks, and it conforms well with empirical evidence. A complete empirical analysis demonstrating the reciprocal causality between inter-bank correlations and information contagion is called for. We are currently formulating such an empirical test. We plan to measure herding and spillover using the Merton-style inversion of the correlation of bank equity returns into the correlation of bank asset values over “ex-ante” and “ex-post” periods.

The interaction between the two forms of systemic risk renders the identification of its welfare costs somewhat tricky. In future theoretical work, we plan to introduce firms, that is, the real sector, into the model. This would enable a richer welfare analysis of herding and contagion. Furthermore, we also plan to introduce a market for risk-free bonds, whereby the model can study the effect of flight to quality and bank failures on the spread between bank borrowing rates and risk-free rates. A final step in the model development would include considering the general equilibrium where depositors’ choice of assets is also endogenized. Characterization of optimal prudential bank regulation in such a setting designed to mitigate the welfare costs of bank herding to the real sector and to the depositors appears to be challenging but fruitful objective to pursue.

Figure 1: Critical Values for Constraints

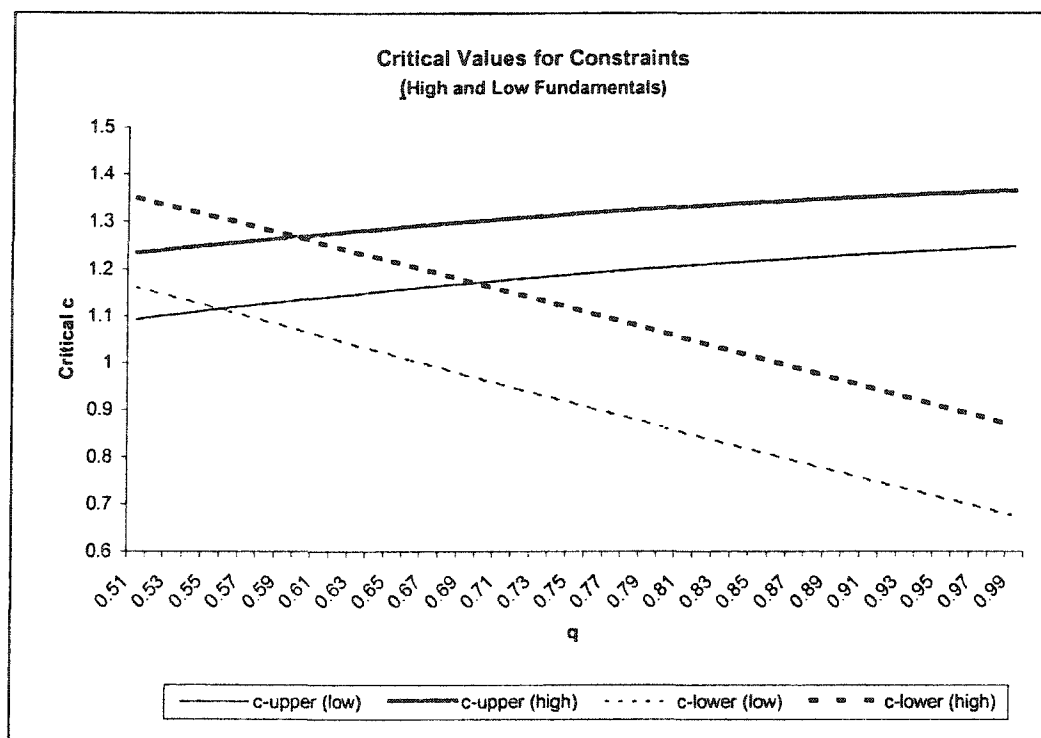


Figure 2: Expected Utility from Run and No-Run Contracts

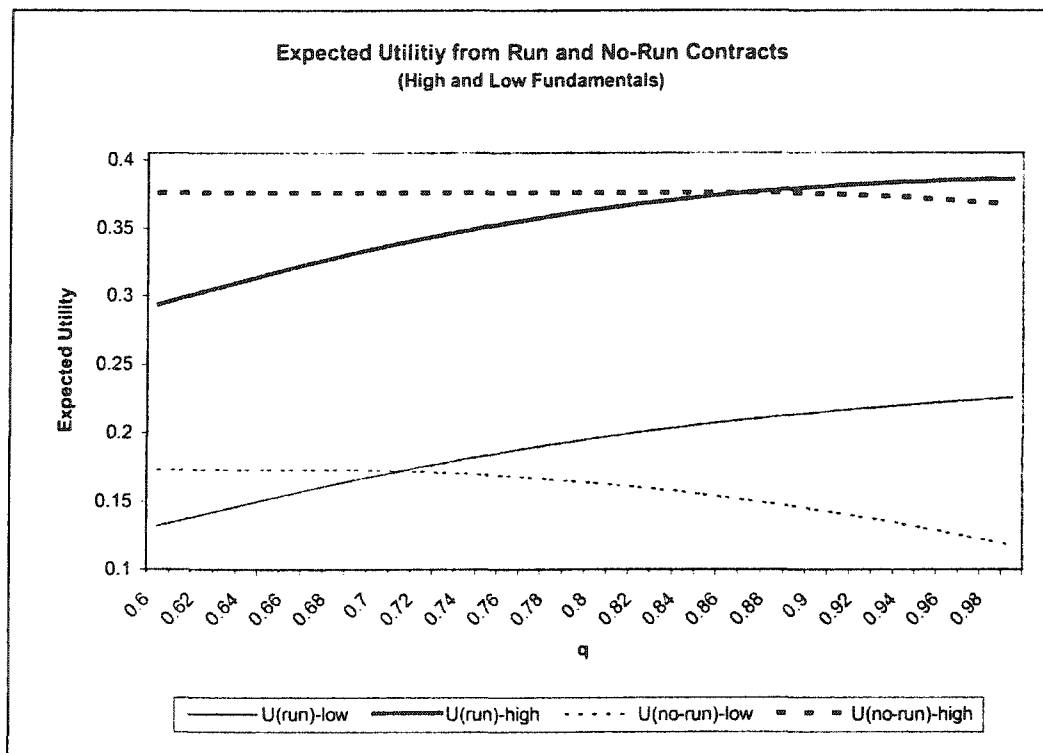


Figure 3: Sequence of Events 1

$t = 0$	$t = 1$	$t = 2$
· Nature chooses the state. · Banks choose the deposit contract to offer. · Depositors make their investment choices. · Bank chooses the portfolio of assets.	· Depositors learn their type and receive private signals. · Depositors make their withdrawal decisions. · If there is no run, early depositors get their promised. · If there is a run, bank cumulates withdrawals.	· Returns are realized. · Late depositors who did not withdraw their return.

Figure 4: Actions Chosen in the First Round

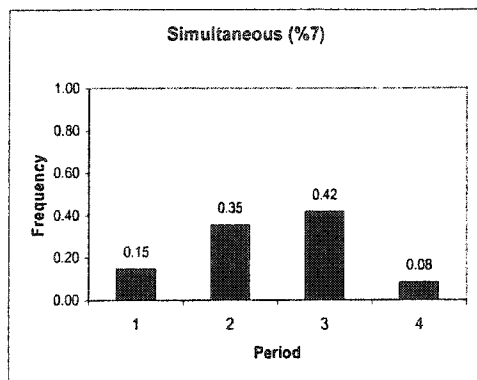


Figure 4a

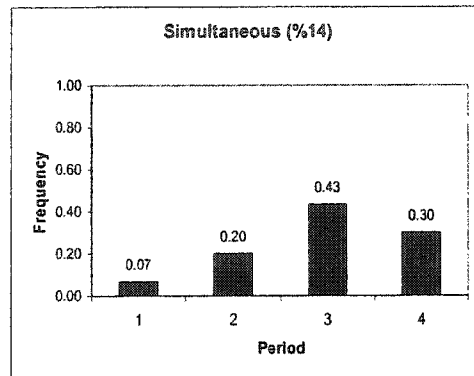


Figure 4d

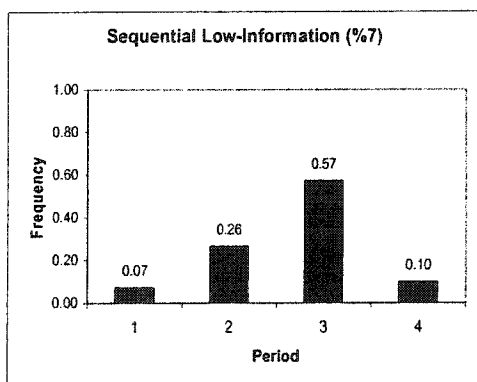


Figure 4b

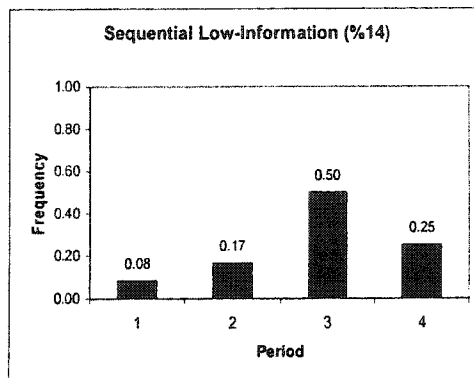


Figure 4e

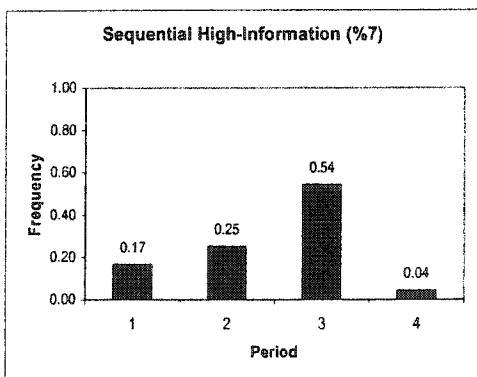


Figure 4c

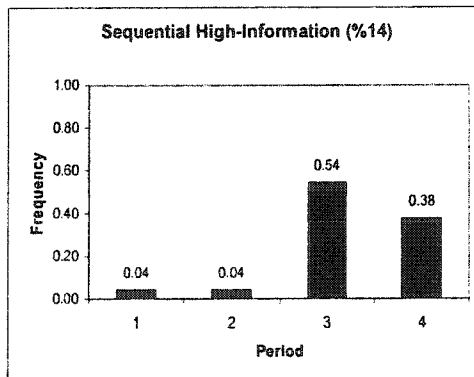


Figure 4f

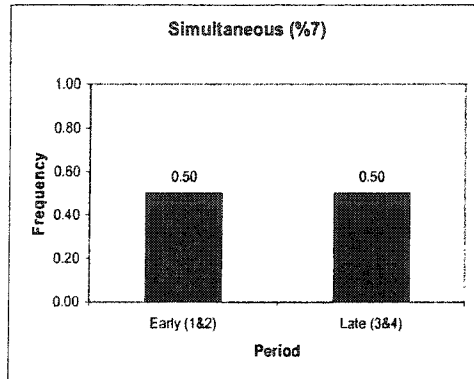


Figure 4g

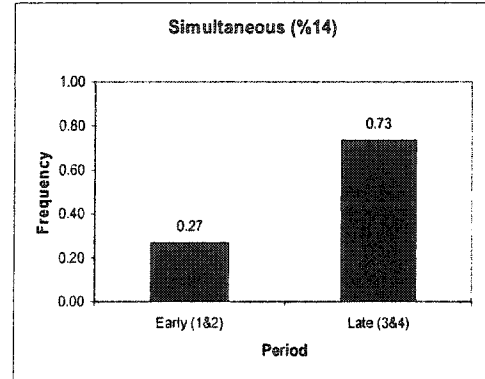


Figure 4j

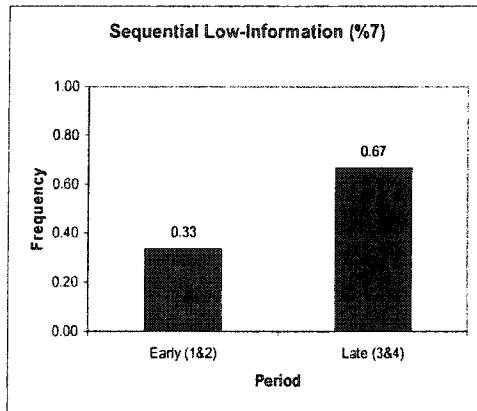


Figure 4h

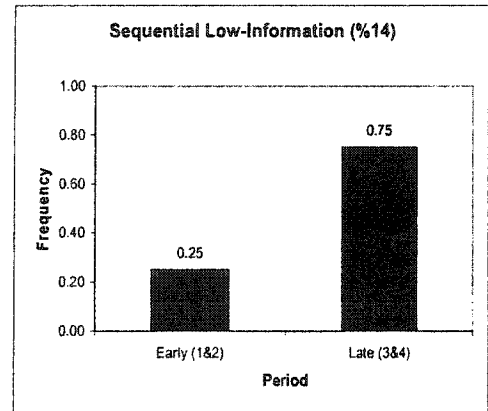


Figure 4k

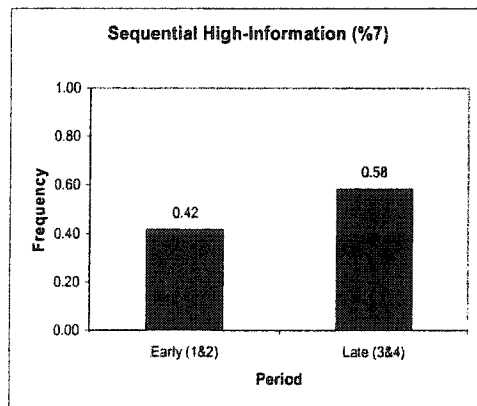


Figure 4i

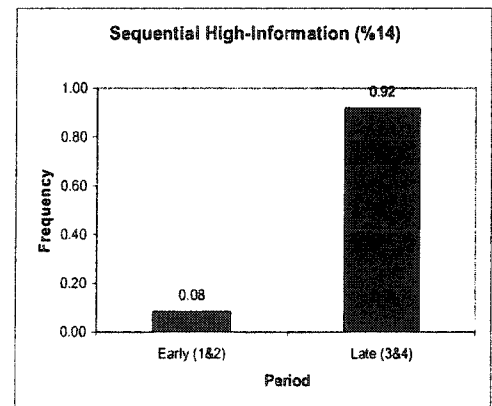


Figure 4l

Figure 5: Effect of Different Levels of Insurance on Withdrawal Times

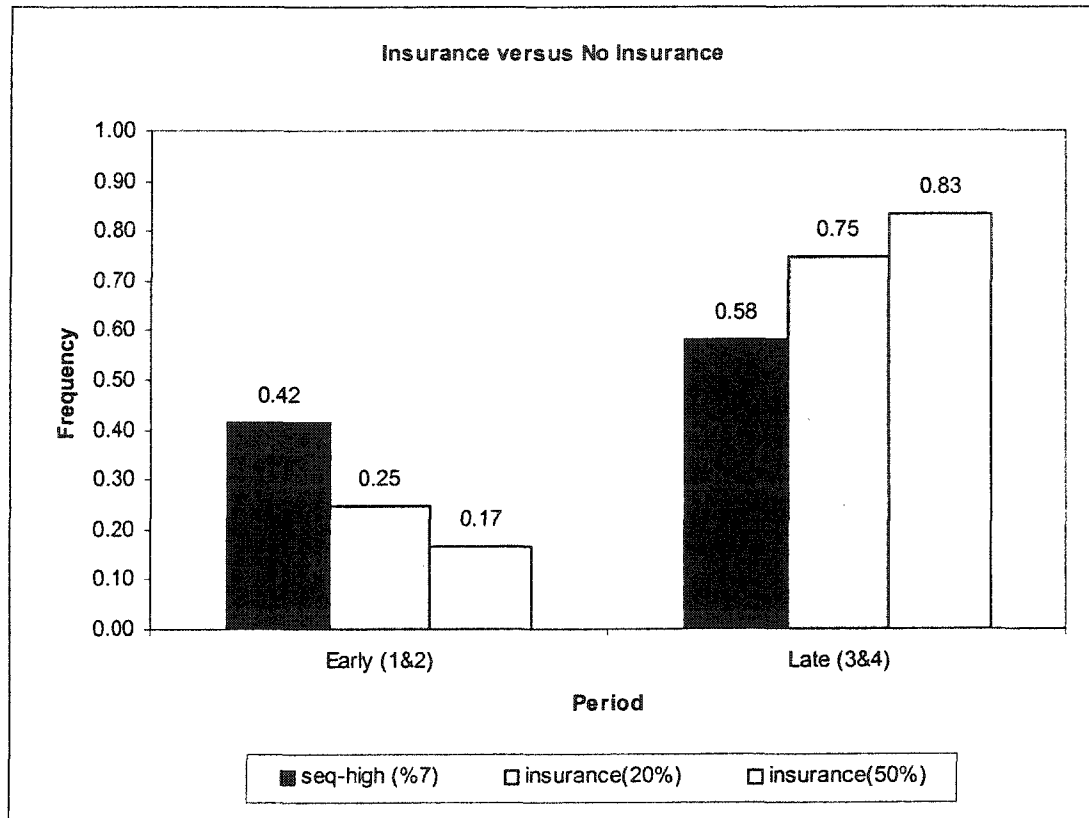


Figure 6: Withdrawal Choices: Symmetric vs. Asymmetric Information

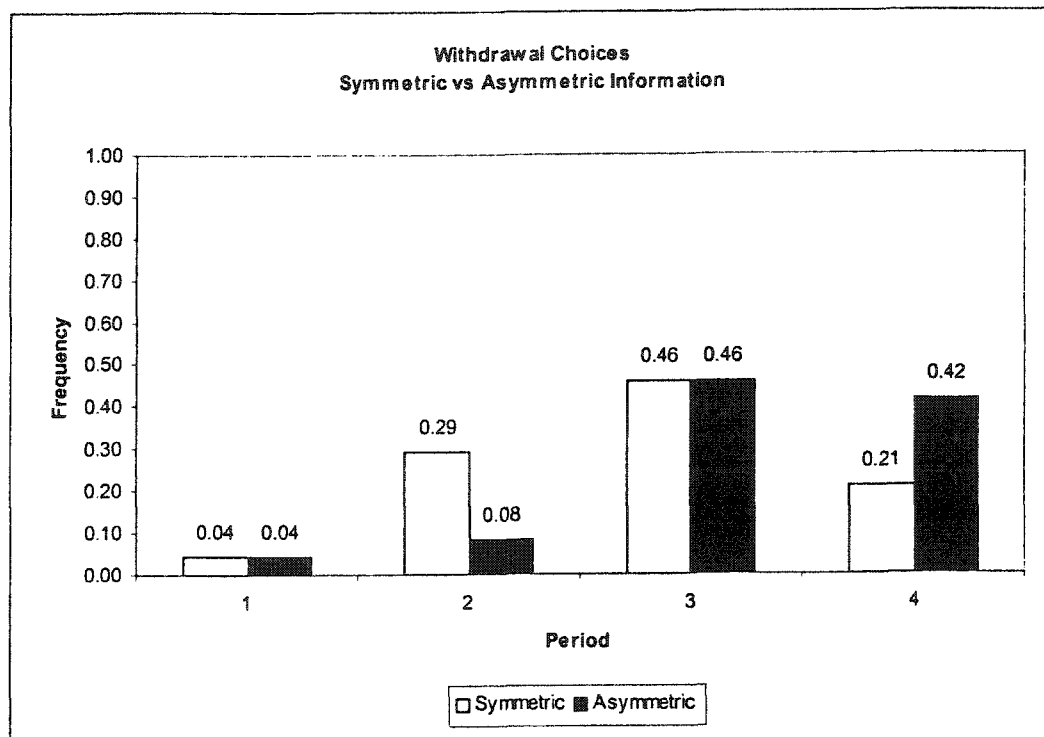


Figure 7: Informed Players' Choices as a Function of Bank

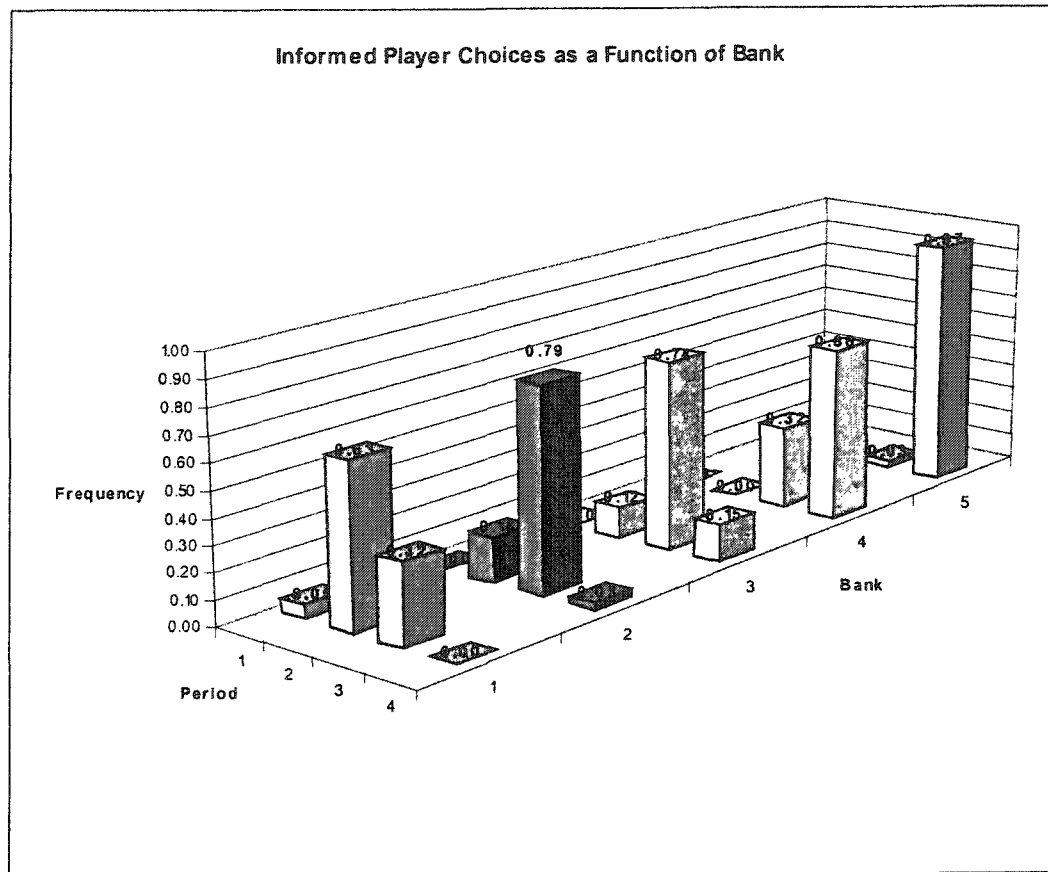


Figure 8: Withdrawal Choices: Uninformed and Symmetrically Informed Subjects

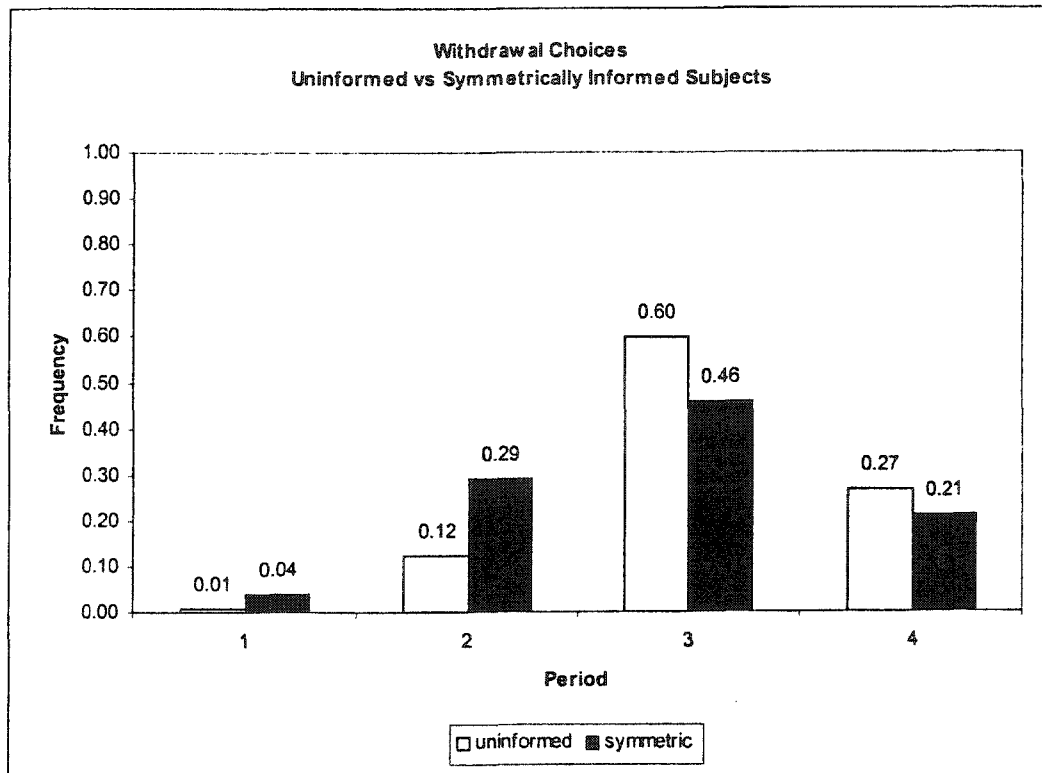


Figure 9: Sequence of Events 3

$t = 0$	$t = 1$	$t = 2$
Nature chooses the state (Good or Bad).	Returns are realized.	Returns are realized.
Banks choose the level of correlation (c).	Banks with the low return are liquidated	State is realized.
	Banks with the high return invest again.	

Table 1: Payoffs for Early and Late Depositors with Public Information

state\outcome	c_1	c_2
R	$\frac{L}{\lambda}$	$\frac{XR}{1-\lambda}$
r	$L + rX$	$L + rX$

Table 2: Probabilities of Signals Conditional on State

state\signal	Good	Bad
$\tilde{R} = R$	q	$1 - q$
$\tilde{R} = r$	$1 - q$	q

Table 3: Probabilities of Cascades in the Good State

	<i>No-Run Cascade</i>	<i>No Cascade</i>	<i>Run Cascade</i>
$i = 2$	q	$(1 - q)q$	$(1 - q)^2$
$i = n$	$q [(1 - q)q]^{(n/2)-1}$	$[(1 - q)q]^{(n/2)}$	$(1 - q)^2 [(1 - q)q]^{(n/2)-1}$

Table 4: Probabilities of Run and No Run in Different States

state\outcome	No Run	Run
Good	$\frac{q}{1-q(1-q)}$	$\frac{(1-q)^2}{1-q(1-q)}$
Bad	$\frac{1-q}{1-q(1-q)}$	$\frac{q^2}{1-q(1-q)}$

Table 5: Payoffs from not Withdrawing on Player's Turn

	<i>No-Run Cascade</i>	<i>No Cascade</i>	<i>Run Cascade</i>
$i = 2$	q	$(1 - q)q$	$(1 - q)^2$
$i = n$	$q [(1 - q)q]^{(n/2)-1}$	$[(1 - q)q]^{(n/2)}$	$(1 - q)^2 [(1 - q)q]^{(n/2)-1}$

**Table 6: Payoffs from not Withdrawing on Player's Turn with
Liquidity Support.**

state\outcome	No Run	Run
Good	$\frac{q}{1-q(1-q)}$	$\frac{(1-q)^2}{1-q(1-q)}$
Bad	$\frac{1-q}{1-q(1-q)}$	$\frac{q^2}{1-q(1-q)}$

Table 7: Experimental Design

Experiment	Form	Information	Rounds	Subjects	Equilibria
$r^*=7\%$	Simultaneous	NA	21	48 (8 groups)	(6,0,0,0) (0,6,0,0)
$r^*=14\%$	Simultaneous	NA	21	30 (5 groups)	(0,0,6,0) (0,0,0,6)
$r^*=7\%$	Sequential	Low, Symmetric	21	42 (7 groups)	(6,0,0,0) (0,6,0,0)
$r^*=7\%$	Sequential	High, Symmetric	21	24 (4 groups)	(6,0,0,0) (0,6,0,0)
$r^*=7\%$ (20% Insurance)	Sequential	High, Symmetric	21	24 (4 groups)	(6,0,0,0) (0,6,0,0)
$r^*=7\%$ (50% Insurance)	Sequential	High, Symmetric	21	24 (4 groups)	(0,6,0,0)
$r^*=14\%$	Sequential	Low, Symmetric	21	24 (4 groups)	(0,0,6,0) (0,0,0,6)
$r^*=14\%$	Sequential	High, Symmetric	21	24 (4 groups)	(0,0,6,0) (0,0,0,6)
$r^*=8\%$	Sequential	High, Symmetric	21	24 (4 groups)	(0,6,0,0)
$r^*=8\%$	Sequential	High, Asymmetric	21	24 (4 groups)	NA ⁺

⁺ Equilibria here are defined as functions and described in the paper.

Table 8: Withdrawal Times: With and Without Insurance

Experiment/Period	1	2	3	4
No Insurance	.17	.25	.54	.04
20% Insurance	.04	.21	.67	.08
50% Insurance	.00	.17	.75	.08

Table 9: Frequency of Withdrawals in the First and Last 5 Rounds

	Rounds	Period 1	Period 2	Period 3	Period 4
Simultaneous (7%)	First 5	0.08	0.42	0.43	0.07
	Last 5	0.18	0.32	0.44	0.07
Sequential-Low (7%) ($z = 1.8, p = 0.04$)	First 5	0.10	0.35	0.41	0.14
	Last 5	0.06	0.51	0.36	0.07
Sequential-High (7%)	First 5	0.11	0.36	0.43	0.10
	Last 5	0.04	0.37	0.50	0.09
Insurance 20% ($z = 2.6, p = 0.005$)	First 5	0.04	0.27	0.50	0.19
	Last 5	0.03	0.43	0.45	0.09
Insurance 50%	First 5	0.06	0.29	0.48	0.17
	Last 5	0.03	0.45	0.43	0.10
Simultaneous (14%) ($z = -3.73, p = 0.0001$)	First 5	0.02	0.17	0.39	0.42
	Last 5	0.00	0.00	0.43	0.58
Sequential-Low (14%) ($z = -2.52, p = 0.006$)	First 5	0.04	0.23	0.38	0.35
	Last 5	0.02	0.05	0.52	0.41
Sequential-High (14%) ($z = -3.61, p = 0.0002$)	First 5	0.04	0.11	0.48	0.38
	Last 5	0.01	0.03	0.39	0.58
Sequential-High (8%)	First 5	0.04	0.24	0.57	0.15
	Last 5	0.01	0.22	0.72	0.06
Asymmetric	First 5	0.03	0.08	0.55	0.33
	Last 5	0.01	0.07	0.41	0.41

**Table 10: Joint Probabilities of Returns and States for an
Individual Bank**

state\return	High	Low
Good	pq	$p(1 - q)$
Bad	$(1 - p)(1 - q)$	$(1 - p)q$

Table 11: Joint Distribution of Bank Returns in the Good State

$A \setminus B$	High	Low
High	c	$q - c$
Low	$q - c$	$1 - 2q + c$

Table 12: Joint Distribution of Bank Returns in the Bad State

$A \setminus B$	High	Low
High	$1 - 2q + c$	$q - c$
Low	$q - c$	c

Table 13: Possible Outcomes from First Period Investments

Bank $A \setminus$ Bank B	High	Low
High	SS	SF
Low	FS	FF

Table 14: Bank A's Second-Period Profits Based on the First
Period Outcomes

Bank A\Bank B	High	Low
High	$\pi_2^{ss} > \pi_2^{sf}$	π_2^{sf}
Low	0	0

Table 15: Joint Returns to Firms Under Information Structure

(A_1, B_1)

Firms for Bank $B \backslash$ Bank A	A_1	A_2
B_1	$(R_1 + \epsilon, R_1 + \epsilon)$	$(R_1, R_1 + \epsilon)$
B_2	$(R_1 + \epsilon, R_1)$	(R_1, R_1)

Table 16: Joint Returns to Firms Under Information Structure

(A_1, B_2)

Firms for Bank $B \backslash$ Bank A	A_1	A_2
B_1	$(R_1 + \epsilon, R_1)$	(R_1, R_1)
B_2	$(R_1 + \epsilon, R_1 + \epsilon)$	$(R_1, R_1 + \epsilon)$

APPENDIX A

Unobserved Types

Here I will relax the assumption that types are observed by the depositors. As explained, this will contribute noise, but the previous results will continue to hold. For all the analysis below, I assume that an informational cascade has not started yet. The following analysis is for the case where the public belief is equal to $1/2$ but it certainly holds for the general case.

If a depositor decides to withdraw at $t = 1$ it can be for two reasons:

i) She may be an early consumer (with probability λ) or

ii) She may be a late consumer and observed a bad signal (with probability $(1 - \lambda) ((1/2)(1 - q) + (1/2)q) = 1/2(1 - \lambda)$).¹⁹

So when a depositor decides to withdraw at $t = 1$, the conditional probability that she is a late consumer and observed a bad signal is :

$$\Pr(s_b|W) = \frac{(1/2)(1 - \lambda)}{\lambda + (1/2)(1 - \lambda)} = \frac{1 - \lambda}{1 + \lambda}.$$

Using the value $\lambda = \frac{1}{2}$, we get:

¹⁹A depositor is a late consumer with probability $(1 - \lambda)$. With probability $1/2$ it is the good state and a late consumer observes a bad signal with probability $(1 - q)$ in the good state. With probability $1/2$ it is the bad state and a late consumer observes a bad signal with probability q in the bad state. Therefore the probability of this case is $(1 - \lambda) ((1/2)(1 - q) + (1/2)q)$.

$$\Pr(s_b|W) = \frac{1/2}{3/2} = \frac{1}{3}.$$

If a depositor does not withdraw, it reveals that she has certainly observed a good signal.

$$\Pr(s_g|N) = 1.$$

In this case early consumers will add extra noise to the model and a withdrawal decision will now be noisy information for the realization of a bad signal.

Let p_N be the conditional probability that we are in the good state, given a non-withdrawal decision. Then we have:

$$p_N = \Pr(\tilde{R} = R|N) = p_g = 1 - q.$$

Let p_W be the conditional probability that we are in the good state given a withdrawal decision. With probability $1/2$ we are in the good state and a depositor withdraws early in the good if she is an early consumer (with probability λ) or if she is a late consumer and observed the bad signal (with probability $(1 - \lambda)(1 - q)$). Therefore

$$\begin{aligned}
p_W &= \frac{(1/2)(\lambda + (1-\lambda)(1-q))}{\lambda + (1/2)(1-\lambda)} \\
&= \frac{1-q(1-\lambda)}{(1+\lambda)}.
\end{aligned}$$

Using the value $\lambda = \frac{1}{2}$, we get:

$$p_W = \frac{2-q}{3}.$$

Claim 2 $\forall \lambda \in (0, 1), p_b = 1 - q < p_W < 1/2$.

P roof. Note that $\frac{\partial p_W}{\partial \lambda} > 0$. When $\lambda = 0$, $p_W = 1 - q = p_b$. When $\lambda = 1$, $p_W = 1/2$. ■

The analysis is similar to that of the case without the early consumers. Since $p_W > p_b$, $p_W(p_g(p)) > p$ so that we will need more than one, (say, k^*) withdrawals to cancel out the effect of a non-withdrawal. We will now have to deal with the cases in which we observe one non-withdrawal and k withdrawals where $k < k^*$. So we will have more cases of interest for the purposes of writing the optimal deposit contract but the analysis will be similar.

APPENDIX B

Proofs for Chapter 2

Proof of Proposition 3 (Informational Invariance):

The proposition is true trivially for the Low-Information Sequential case since the information structures of the two game-forms are identical.

In the Simultaneous case we have proven that the only pure strategy equilibria for our bank run game are the symmetric pure strategy equilibria in which all subjects remove their money at the same time. Now consider an allocation, $\alpha = (\alpha_1, \alpha_2, \alpha_3, \alpha_4)$ of players to removal times in the sequential version that is not an equilibrium in the simultaneous version, where α_t are the number of players who remove their money in period t under allocation α . If this allocation were made in the simultaneous game, we know, by assumption, that at least one player would have an incentive to deviate. Let us look at the best response function for players in the Simultaneous version when they face allocation α .

In the Simultaneous version, players calculate a best response under the assumption that no other player will change his or her removal time so that they can take the actions of the other $n - 1$ players as fixed. We cannot necessarily make this same *ceteris paribus* assumption in the sequential version since if a player decides not to move according to α but to remove his or her money

later, this lack of action will be detected by other players and they may change their actions in response. Hence, such deviating players cannot carry out their best response to α under the assumption that the other $n - 1$ players will stay fixed in their removal times. But that is only the case when a player decides to move later than prescribed by α . If their simultaneous version best response is to move earlier, then they can execute that best response in the sequential form game as well since, while their deviation will be detected, it will be too late for other players to do anything about it since the deviating player will already have her money. Such deviators can maintain the same *ceteris paribus* assumption about the other $n - 1$ players as players in the simultaneous form game. Hence, any deviation from α in the simultaneous form game which suggests that players remove their money earlier can be executed in the sequential form game without being detected and hence will be done. (The same logic applies to players in period 3 who want to remove their money later since while the players who remove their money in period 4 will notice it, they cannot remove their money until the next period and that is too late). So if α is not an equilibrium in the Simultaneous version it will not be an equilibrium for the sequential form game as long as the best response to α in the simultaneous game requires people in any period to remove their money earlier or a period 3 player to remove later. So we only need to consider deviations for subjects who, under configuration α , are supposed to withdraw

their money in periods 1 or 2 but are contemplating a deviation.

The key question, then, is what conjecture will players who are supposed to move in periods 1 and 2 make about the reactions of the other, later-moving players, when they deviate and do not withdraw when they are expected to. To prove our result, we will make the worst possible conjecture from their point of view, which is that if they fail to withdraw when they are expected to, all of the other players will immediately withdraw their money in the very next period. Hence, if configuration α calls for a player to remove his or her money in period 1 and he or she does not do so, we will assume that all of the remaining players (who were called on to remove after period 1) will withdraw in period 2. If it is still worthwhile for the period-1 player to deviate under these circumstances (or for a later moving player to move earlier if the period-1 mover has no incentive to move later), then we know that such a configuration is not an equilibrium.

From inspection of the payoff table for $r^* = .07$, $r' = .12$ (a similar argument can be made for the $r^* = .14$, $r' = .12$ case as well), we can see that for any configuration, α , where 3 or fewer players are expected to remove in period 1, any one of them would have an incentive to deviate to period 2 even under our pessimistic assumption. (They may have even better deviations under alternative assumptions but that fact is not needed in our argument). Hence such a configuration cannot be an equilibrium.

When four or more subjects are expected to withdraw in period 1, then for any configuration of later-moving subjects, at least one of them would want to move earlier. Hence, no configuration in which some, but not all, subjects move in period 1 can be an equilibrium to the High-Information Sequential form game.

Finally, let's look at the case where no subject removes in period 1 but one or more in period 2. Here, we look at configurations in which the earliest a subject is supposed to move is period 2. However, the same argument will establish the result here as well.

Proof of Proposition 4 (Insider Information and Bank Run Severity):

The proof uses certain domination relationships concerning the payoffs to informed subjects to calculate the minimum expected number of periods money will remain in the bank during any separating equilibrium. Since we know that when information is symmetric all subjects withdraw their funds in period 2, if the minimum we calculate is greater than 2 periods, we have proven our result.

We start by showing that if the bank chosen is Bank 3, in any separating equilibrium no informed subject will withdraw in period 1. To show this assume that a separating equilibrium did in fact exist where, conditional on Bank 3, all informed subjects move in period 1. In addition, assume that

such an equilibrium directs the four uninformed subjects to move in period 2. Therefore in this equilibrium we would have the 2 informed subjects moving in period 1 and the 4 uninformed subjects moving right after them in period 2. In this equilibrium the two informed subjects earn 11.2. However, if either of them decided to deviate and withdraw in period 2, they would earn 11.58. They will earn even more if the uninformed had decided to remove their money later. Therefore, assuming that the uninformed move in period 2 is the worst case for the informed subjects given their period 1 move and hence if they find it beneficial to deviate here they will do so under other assumptions. So no separating equilibrium can have informed subjects removing their money in period 1 conditional on knowing the bank is Bank 3. They must withdraw in period 2 or later.

Further, if the bank chosen is Bank 5, it is a dominant strategy for the informed subjects to wait until Period 4. So we have established that in any separating equilibrium when the bank is Bank 3 the withdrawal period cannot be earlier than period 2 while if it is Bank 5 it is dominant to wait until period 4.

Given these facts consider the following proposed strategy pair which has the property that, if it were to actually be an equilibrium, it would be that one with the shortest withdrawal time that respects the two properties we have mentioned above.

Informed: If Bank 1 or Bank 2, withdraw in Period 1. If Bank 3 or Bank 4, withdraw in Period 2. If Bank 5, withdraw in Period 4.

Uninformed: Do not remove money in Period 1. (Since this strategy (removing in period 1) is not conditioned on the behavior of an informed subject, it can never be part of a separating equilibrium). If somebody removes in Period 1, remove in Period 2. If somebody removes in Period 2, remove in Period 3. Otherwise remove in Period 4.

In this worst case scenario, as we see in the table below, the expected length of time money remains in the banking system is 2.11 periods (which is greater than the 2 periods it remains in the system when information is symmetric).

Bank 1	$(2(1) + 4(2))/6 = 5/3$
Bank 2	$(2(1) + 4(2))/6 = 5/3$
Bank 3	$(2(2) + 4(3))/6 = 7/3$
Bank 4	$(2(2) + 4(3))/6 = 7/3$
Bank 5	4
Average	2.11

APPENDIX C

Student Reports

For example, consider the following two statements from the two informed subjects who engaged in our experiment on July 25, 2002 and described their behavior as follows:

Player 1 (Informed)

If it was Bank 1, I withdrew in period 2.

Bank 2: Period 2 or 3 (depending on how many withdrew before me).

Bank 3: Always period 3.

Bank 4 & Bank 5: Always period 4.

Player 4 (Informed)

After observing that no one withdrew ever during the first time period, I withdrew in the 2nd time period for Bank 1. For Bank 3 or 4, I withdrew in the 3rd time period (only when it was Bank 1, did anyone withdraw before the third period - I assume it was me and the other informed player). For Bank 5, I left the money in until the end.

While these strategies were not coordinated, they clearly indicated that their withdrawal times were functions of the bank realization for any period.

For uninformed players it was clear that they attempted to condition their withdrawal on the actions of the informed. For example, consider the following

statements of two of the subjects in the July 25 experiment whose statements best represented the behavior consistent with a separating equilibrium:

Player 2 (Uninformed)

I tried to wait and see what the two informed players were doing. If they got out quickly, so did I. There was also a fair amount of intuition involved. Sometimes I went with the feeling to get out / stick with it when I was unsure of the moves of the informed. I tried to wait until period 4 if the informed had not moved in the first two periods. But sometimes I panicked and got out early.

Player 5 (Uninformed)

Because I was uninformed and knew that 2 were informed, I withdrew as soon as I saw 2 people had withdrawn their money.

The remaining two players had the following to say:

Player3 (Uninformed)

Wait until the last period, only withdraw earlier if people withdrew in the second period. I came up with this strategy only after a couple of rounds.

Player6 (Uninformed)

Waited until not too many people got out. If zero people came out in the first 2 time periods, I hold out till the 3rd period. If people withdrew in the beginning then I cashed out right after them.

APPENDIX D

Proofs for Chapter 3

The following lemmas are employed towards proving the main propositions of the paper.

Lemma D.1 *The probability of a high return, given that both banks had high returns from their first investments, is decreasing in c . Formally, $\frac{\partial \alpha_1}{\partial c} < 0$, $\forall p, q$. In turn, the cost of borrowing is increasing in c , i.e., $\frac{\partial r_1^{ss}}{\partial c} > 0$, $\forall p, q$.*

Proof of Lemma D.1: From equation (3.11), we obtain

$$\begin{aligned} \frac{\partial \alpha_1}{\partial c} = & \frac{[pq + (1-p)(1-q)] [(1-2q)(1-p) + c]}{[(1-2q)(1-p) + c]^2} \\ & - \frac{[pcq + (1-p)(1-q)(1-2q + c)]}{[(1-2q)(1-p) + c]^2} \end{aligned}$$

which is negative, since the numerator equals $-p(1-p)(1-2q)^2$, which is always less than zero. Using the expression for r_1^{ss} and the fact that $u'(\cdot) > 0$, it follows that $\frac{\partial r_1^{ss}}{\partial c} > 0$. $\diamond$

Lemma D.2 *When banks are perfectly correlated, the probability of a high return, given that both banks had high returns from their first investments, is greater than the prior probability of a high return. Formally, $\alpha_1(c_{\max}) > \alpha_0$, $\forall p, q$.*

Proof of Lemma D.2: From equations (3.5) and (3.11), the claim reduces

to showing that

$$\alpha_1(q) = \frac{pq^2 + (1-p)(1-q)^2}{pq + (1-p)(1-q)} > \alpha_0 = pq + (1-p)(1-q).$$

This holds since $pq^2 + (1-p)(1-q)^2 - [pq + (1-p)(1-q)]^2 = p(1-p)(2q-1)^2 > 0$.

◇

These lemmas and the maintained assumption that $u'(\cdot) > 0$ imply the following result.

Lemma D.3 $\forall p, q$, and c , $\alpha_1(c) > \alpha_0$ and $r_1^{ss} < r_0$.

Proof of Proposition 5: The three parts of the proposition are a consequence of Lemma D.3 and the expressions for second-period profits in states SS and SF (equations 3.14 and 3.16, respectively). ◇

Proof of Proposition 6: We need to consider two cases as discussed in Section 3.6. We will prove the case where $R_1 \geq r_0$. The other case, $R_1 \in (r_1^{ss}(q), r_0]$, can be proved the same way.

When $R_1 \geq r_0$ from equation 3.20, the expected second-period profits are

$$E(\pi_2(c)) = [pq^2 + (1-p)(1-q)^2] [R_1 - (\lambda(c)r_1^{ss}(c) + (1-\lambda(c))r_0)].$$

We wish to show that

$$\frac{\partial E(\pi_2(c))}{\partial c} = - [pq^2 + (1-p)(1-q)^2] \left[\frac{\partial \lambda(c)}{\partial c} (r_1^{ss}(c) - r_0) + \lambda(c) \frac{\partial r_1^{ss}(c)}{\partial c} \right]$$

is greater than zero. Since $[pq^2 + (1-p)(1-q)^2] > 0$, the sign of the expression above is determined by the sign of the expression inside the second set of square brackets on the right hand side of the above equation. We prove this in steps:

(i) From the expression for $\lambda(c)$ in equation 3.21, it follows that

$$\frac{\partial \lambda(c)}{\partial c} = \frac{pq + (1-p)(1-q)}{pq^2 + (1-p)(1-q)^2} .$$

(ii) From equations 3.11 and 3.13, it follows that

$$u(r_1^{ss}(c)) = \frac{(1-2q)(1-p) + c}{pcq + (1-p)(1-q)(1-2q+c)} .$$

Taking the partial derivative of both sides with respect to c , we get

$$\begin{aligned} u'(\cdot) \frac{\partial r_1^{ss}(c)}{\partial c} &= \frac{[pcq + (1-p)(1-q)(1-2q+c)]}{[pcq + (1-p)(1-q)(1-2q+c)]^2} \\ &\quad - \frac{[(1-2q)(1-p)+c][pq + (1-p)(1-q)]}{[pcq + (1-p)(1-q)(1-2q+c)]^2} \\ &= \frac{p(1-p)(1-2q)^2}{[pcq + (1-p)(1-q)(1-2q+c)]^2}. \end{aligned}$$

Therefore, we obtain that

$$\begin{aligned} \lambda(c) \frac{\partial r_1^{ss}(c)}{\partial c} &= \frac{1}{u'(r_1^{ss}(c))} \cdot \\ &\quad \frac{p(1-p)(1-2q)^2}{[pq^2 + (1-p)(1-q)^2][pcq + (1-p)(1-q)(1-2q+c)]} \end{aligned}$$

(iii) Finally, we obtain

$$\frac{\partial \lambda(c)}{\partial c} (r_1^{ss}(c) - r_0) = \frac{pq + (1-p)(1-q)}{pq^2 + (1-p)(1-q)^2} \left[u^{-1} \left(\frac{1}{\alpha_1} \right) - u^{-1} \left(\frac{1}{\alpha_0} \right) \right].$$

Let $v = u^{-1}$. Since $u(\cdot)$ is increasing and concave, $v'(\cdot) > 0$ and $v''(\cdot) < 0$.

Thus,

$$\left[v \left(\frac{1}{\alpha_1} \right) - v \left(\frac{1}{\alpha_0} \right) \right] < v' \left(\frac{1}{\alpha_1} \right) \left(\frac{1}{\alpha_1} - \frac{1}{\alpha_0} \right).$$

Substituting for α_0 and α_1 ,

$$\begin{aligned}
v' \left(\frac{1}{\alpha_1} \right) \left(\frac{1}{\alpha_1} - \frac{1}{\alpha_0} \right) &= \frac{1}{u'(r_1^{ss}(c))} \cdot \\
&\quad \left[\frac{\frac{(1-2q)(1-p)+c}{pcq+(1-p)(1-q)(1-2q+c)}}{-\frac{1}{pq+(1-p)(1-q)}} \right] \\
&= -\frac{1}{u'(r_1^{ss}(c))} \cdot \\
&\quad \left\{ \left(\frac{p(1-p)(1-2q)^2}{[pcq+(1-p)(1-q)(1-2q+c)]} \right) \cdot \right. \\
&\quad \left. \left(\frac{1}{pq+(1-p)(1-q)} \right) \right\}.
\end{aligned}$$

Therefore,

$$\begin{aligned}
\frac{\partial \lambda(c)}{\partial c} (r_1^{ss}(c) - r_0) &< -\frac{1}{u'(r_1^{ss}(c))} \cdot \frac{1}{(pq^2 + (1-p)(1-q)^2)} \cdot \\
&\quad \left[\frac{p(1-p)(1-2q)^2}{[pcq+(1-p)(1-q)(1-2q+c)]} \right] \\
&< -\lambda(c) \frac{\partial r_1^{ss}(c)}{\partial c}.
\end{aligned}$$

Using steps (i), (ii) and (iii) above, it follows that

$$\frac{\partial \lambda(c)}{\partial c} (r_1^{ss}(c) - r_0) + \lambda(c) \frac{\partial r_1^{ss}(c)}{\partial c} < 0.$$

It follows that in either of the cases, $R_1 \in (r_1^{ss}(q), r_0]$ or $R_1 \geq r_0$, $E(\pi_2(c))$ is increasing in c , and thus banks pick the highest possible inter-bank correlation

$$c_{max} = q. \quad \diamond$$

Proof of Proposition 7: For the case with flight to quality, the first-order condition for the choice of inter-bank correlation is

$$\frac{\partial E(\pi_2^{FQ})}{\partial c} = \frac{\partial E(\pi_2)}{\partial c} - \alpha_0 (R_1 - r_0)^+.$$

We prove the proposition in parts.

(i) From Proposition 6, we know that $\frac{\partial E(\pi_2)}{\partial c} > 0$. Thus, for values of $R_1 \leq r_0$, $\frac{\partial E(\pi_2^{FQ})}{\partial c} = \frac{\partial E(\pi_2)}{\partial c} > 0$. That is, banks choose the highest possible inter-bank correlation $c_{max} = q$.

The rest of the proof deals with values of $R_1 > r_0$, the case where the surviving bank is viable in states SF and FS .

(ii) Let $\frac{\partial E(\pi_2)}{\partial c}(c_{max})$ denote the value of the partial derivative of the expected second period profit (in absence of flight to quality) with respect to c , at $c_{max} = q$. Define

$$R_1^* = \left[\frac{\partial E(\pi_2)}{\partial c}(c_{max}) / \alpha_0 \right] + r_0.$$

Then, at R_1^* , $\frac{\partial E(\pi_2^{FQ})}{\partial c}(c_{max}) = 0$, and, for $R_1 \leq R_1^*$, $\frac{\partial E(\pi_2^{FQ})}{\partial c}(c_{max}) > 0$. Thus, banks choose the highest possible inter-bank correlation $c_{max} = q$ for $R_1 \leq R_1^*$.

(iii) Similarly, for $R_1 > R_1^*$, $\frac{\partial E(\pi_2^{FQ})}{\partial c}(q) < 0$, so that banks choose a level of

c that is less than c_{max} . Now, define

$$R_1^{**} = \left[\left(\max_c \frac{\partial E(\pi_2)}{\partial c} \right) / \alpha_0 \right] + r_0.$$

Note that $R_1^* \leq R_1^{**}$. For values of $R_1 > R_1^{**}$, $\frac{\partial E(\pi_2^{FQ})}{\partial c} < 0$ for all possible c , so that banks choose the lowest possible inter-bank correlation $c_{min} = 2q - 1$.

(iv) Finally, for $R_1 \in (R_1^*, R_1^{**})$, banks choose an interior level of correlation.

To see this, note that $\exists k_1 > 0$ such that for $R_1 \in (R_1^*, R_1^* + k_1)$, $\frac{\partial E(\pi_2^{FQ})}{\partial c}(c_{min}) > 0$ and $\frac{\partial E(\pi_2^{FQ})}{\partial c}(c_{max}) < 0$. By the continuity of $\frac{\partial E(\pi_2^{FQ})}{\partial c}$ and the intermediate-value theorem, it follows that $\exists c^*(R_1) \in (c_{min}, c_{max})$ such that $\frac{\partial E(\pi_2^{FQ})}{\partial c}(c^*) = 0$.

Similarly, $\exists k_2 > 0$ such that, for $R_1 \in (R_1^{**} - k_2, R_1^{**})$, $\frac{\partial E(\pi_2^{FQ})}{\partial c}(c_{min}) < 0$ and $\frac{\partial E(\pi_2^{FQ})}{\partial c}(c_{max}) > 0$. Since $\frac{\partial E(\pi_2^{FQ})}{\partial c}$ is continuous in c , the intermediate-value theorem implies that $\exists c^*(R_1) \in (c_{min}, c_{max})$ such that $\frac{\partial E(\pi_2^{FQ})}{\partial c}(c^*) = 0$.

The above facts follow from the definitions of R_1^* and R_1^{**} . Next, observe that, from the envelope theorem for $c^*(R_1)$ to maximize $E(\pi_2^{FQ})$, we obtain

$$\text{sign} \left(\frac{\partial c^*}{\partial R_1} \right) = \text{sign} \left(\frac{\partial^2 E(\pi_2^{FQ})}{\partial c \partial R_1} \right) = -\alpha_0 < 0$$

since from Proposition 6, $\frac{\partial E(\pi_2)}{\partial c}$ is independent of R_1 . It follows that $c^*(R_1)$ is monotonically decreasing in R_1 and hence, for all $R_1 \in (R_1^*, R_1^{**})$, $c^*(R_1) \in (c_{min}, c_{max})$.

Steps (i)–(iv) together prove all parts of the proposition. $\diamond$

Proof of Proposition 8: We prove Part (ii) of the proposition which is less direct than Part (i). Part (i) follows along similar lines. We focus below only on pure strategy equilibria. Consider the information structure (A_1, B_2) described in Table 16. Suppose bank A lends to firm A_1 . Consider the best-response of bank B . If bank B lends to firm B_1 , then inter-bank correlation is $c = q$, and its loan return in high state is R_1 . By lending to firm B_2 , the inter-bank correlation is $c = q^2$, and bank B 's loan return in high state is $(R_1 + \epsilon)$. Since the first-period profits are constant, the best-response of bank B is determined by its expected second-period profits under the two cases. From equation 3.20, these profits are, respectively,

$$E(\pi_2(q)) = [pq^2 + (1-p)(1-q)^2] (R_1 - h(q)), \text{ and} \quad (\text{D.1})$$

$$E(\pi_2(q^2)) = [pq^2 + (1-p)(1-q)^2] (R_1 + \epsilon - h(q^2)), \text{ where} \quad (\text{D.2})$$

$$h(c) = \lambda(c)r_1^{ss}(c) + (1 - \lambda(c))r_0 \quad (\text{D.3})$$

and $\lambda(c)$ is defined in equation 3.21. In the proof of Proposition 6, we showed that $h'(c) < 0$. Hence, $h(q^2) > h(q)$, and it follows that

$$E(\pi_2(q)) - E(\pi_2(q^2)) = [pq^2 + (1-p)(1-q)^2] (h(q^2) - h(q) - \epsilon)$$

is greater than zero iff $\epsilon < \epsilon^* \equiv h(q^2) - h(q)$.

If $\epsilon > \epsilon^*$, it is a strictly dominant strategy for each bank to invest in the firm in the more profitable industry, A_1 and B_2 in this case. Therefore, when $\epsilon > \epsilon^*$, the game has a unique Nash equilibrium where each bank invests in the more profitable firms.

If $\epsilon < \epsilon^*$, the gain from high correlation is higher than the differential payoff, therefore banks will invest in firms in the same industry.

It can be verified now that if $\epsilon < \epsilon^*$, then bank A lending to firm A_1 and bank B lending to firm B_1 is a Nash equilibrium, and, similarly, bank A lending to firm A_2 and bank B lending to firm B_2 is also a Nash equilibrium. Under the first equilibrium of this coordination problem, bank A makes greater expected profits than does bank B . The exact converse holds under the second equilibrium. Hence, these equilibria are not Pareto-ranked. If $\epsilon > \epsilon^*$, there is exactly one Nash equilibrium in which bank A lends to firm A_1 and bank B lends to firm B_2 . This proves Part (ii) of the proposition.

Constructing the best-responses of both banks under the information structure (A_1, B_1) reveals that if $\epsilon > \epsilon^*$, then there exists only one Nash equilibrium where bank A lends to firm A_1 and bank B lends to firm B_1 . If $\epsilon < \epsilon^*$, then in addition to this equilibrium there is another Nash equilibrium where bank A lends to firm A_2 and bank B lends to firm B_2 . However, this latter equilibrium is Pareto-dominated by the first equilibrium where banks derive benefit from

herding as well as from the superior returns on the firms they lend to. $\diamond$

Proof of Proposition 9: Consider the objective function of the constrained planner. The planner puts optimally designed weights on the welfare of depositors and bank owners. However, if the deposit contract is taken as given by the planner, then in our model depositors earn simply their reservation utility of 1 in each period. It follows that for all possible weights in the planner's objective on the welfare of depositors and bank owners, the planner's choice of inter-bank correlation c maximizes the expected profits of bank owners, which are equal to $[E(\pi_1) + E(\pi_2(c))]$ summed over both banks. By symmetry, this is tantamount to the objective function

$$\max_c [E(\pi_1) + E(\pi_2(c))]$$

which in turn is the objective function of each bank's owners. It follows thus that the investment choices of banks are constrained efficient in our model. $\diamond$

APPENDIX E

Instructions

This is an experiment in group decision-making. A number of research foundations have funded this research and if you make good decisions you might be able to earn a considerable amount of money, which we will arrange to pay you when the experiment is over.

In these instructions we will first explain the decision problem you will engage in and then explain the experimental procedures you will use during the experiment.

The Decision Problem

The decision problem you will engage in has the following structure. As you entered the lab you were randomly assigned to a group of six subjects who will be in your group for the entire 21 rounds of the experiment. In each round you will start out with 10 units of an experimental currency called francs which you must deposit in a "bank" which has promised to pay you compounded interest on your money at the rate of $r' = 12\%$ compounded at the end of each period. (These experimental francs will be converted into dollars at the end of the experiment at the rate of 1 franc = \$1 in round 1 and 1 franc = \$0.05 [five cents] in rounds 2-21. In other words, round 1 is twenty times as valuable to you as rounds 2-21).

The bank will pay you interest on your money until you withdraw it (at which time you will get your 10 francs back as well) but the longest you can keep your money in the bank is 4 periods. This means that if you keep your money in the bank for four periods and then withdraw it, if the bank has enough deposits to pay you, you will earn

$V = X (1 + .12)^4$ francs. The table below tells you how much you will earn if you deposited 10 francs in the bank before period 1 and withdraw it at the end of any of the four periods available and the bank has the funds to pay you. We will assume that the bank promises to pay you $r' = 12\%$ on your money:

Promised Returns	
Date of Withdrawal	Payment
1	11.20
2	12.54
3	14.04
4	15.73

Looking at the table above we see that, at the promised rate of return, if you kept your money in the bank for four periods you would receive 15.73 francs, which is

your original amount of 10 francs compounded at the rate 12% for four periods. If you withdraw your money earlier, say in period 2, you would obviously receive less, i.e., 12.54 francs. **All this assumes that the bank is able to pay you.**

There are several reasons why the bank may not be able to pay you when you decide to withdraw and we will review them now.

First banks make money by borrowing from their clients at low interest rates and lending at higher ones. When you deposit your money in a bank they borrow from you and they promise to pay an interest rate which we are calling r' (this is the cost of the bank) and they hope to find investment opportunities that will return them at least that. If they don't, they will lose money. Therefore, the ability of a bank to be able to pay you what is promised depends on how the bank has invested its money, i.e. on its rate of return compared to what it promised to pay its depositors.

Put differently, let us assume that there are different quality banks in the world and you do not know what the quality of your bank is. A bank's quality measures the rate of return on its investments. More specifically, say there are 5 different qualities of banks that you could have invested your money in. **You will not be told the quality of your bank but you will be told the average quality or average rate of return of the five banks which we will call r^* .** So if r^* is the average or mean rate of return for banks in this five- bank banking industry, then we will assume that one bank will have a rate of return of $3/3(r^*)$ (this will be the average bank), one will have a rate of return of $2/3(r^*)$, one will have a rate of return of $1/3(r^*)$ (these are the less than average banks), one will have a rate of return of $4/3(r^*)$, and one will have a rate of return of $5/3(r^*)$ (these are the above average banks). Which bank your money is in will not be told to you but we will tell you that the probability that your money is in any one of these five banks is equal. In other words, your money is equally likely to be in the average bank as it is in the worst bank yielding a return of $1/3(r^*)$ as it is to be in the bank yielding the highest return of $5/3(r^*)$, each has a $1/5$ chance of occurring. We will call these banks, Banks 1, 2, 3, 4, and 5 with Bank 1 being that bank having the lowest rate of return ($(1/3)r^*$) and Bank 5 having the highest ($5/3r^*$).

So one factor that determines if the bank will be able to pay you your promised rate of return is whether the rate of return in the bank where your money is deposited is greater than the promised rate of return. If it is, then you will be able to get your 10 francs plus interest back whenever you want it, even if you keep it for four periods.

Another way to look at this is say that the average rate of return in the banking industry turns out to be 5% while the promised rate is 4.8%. Then there will be three banks such that if your money was deposited there you would be able to keep it in the bank for four periods and be sure to get paid your promised amount when you withdraw it. These are the average bank, and the two above average banks. Since

there are five banks in total, the probability of being sure to get your promised return in this situation is $3/5 = 60\%$. If the promised rate of return was 5.1%, then only the two above average banks would be able to pay off as promised in any period no matter what people do, and this would have a $2/5 = 40\%$ chance of occurring but there will be a 60% chance that when you go to withdraw your money from the bank, it will not be able to pay you what you were promised.

When the bank is not able to pay you what it promised, how much money you will eventually get will depend on when (what period) you take your money out of the bank and on how many people withdrew their money either before or at the same time as you. Your bank's payment rule can be summarized as follows: **"Pay the promised return on any funds requested to be withdrawn if there is enough money in the bank to do so. If there is not, divide up what is available amongst those requesting payment"**

So, the longer your money is kept in the bank the more it grows because of compound interest. However, if during that period others take their money out they may leave insufficient funds for you especially if your money is deposited in a poor quality bank.

So whether you are able to receive your promised amount of money when you choose to withdraw it depends on the average rate of return in the banking industry because the higher that is the higher the return in your bank is no matter which bank your money is deposited in, and the number of people taking their money out before you. (Obviously you don't care how many of them take it out after you). The higher the rate of return, the more likely it is that you will be able to be paid when you want your money. The more people who withdraw before you the less likely you are to be paid.

Note, however, that whenever the rate of return in the bank you deposited your money in is greater than the promised rate of return, then you will be paid your promised amount for sure no matter when you or anyone else withdraws their money. You only need to worry that you will not be paid when your bank has a rate of return on its investments less than your promised rate r' .

Payoff Tables and Calculators

To help you understand the tradeoffs that exist here we will provide you with two things. First we will provide you with a set of tables marked **Period 1, Period 2, Period 3, and Period 4**, that will tell you how much you will be able to earn or what your payoff will be depending on various scenarios about the behavior of the other subjects in the experiment and on what bank your money happens to be deposited in. Put differently, these tables will tell you your payoff depending upon when you and

everyone else decide to take out your money and which one of the five banks your money is in. We also show your expected or average payoff where the average is taken by incorporating the probability that your money is in any one of the five banks it can be in. (Remember, your money has an equally likely chance of being in any of five banks (Banks 1, ...,5) whose return is either 1/3, 2/3, 3/3, 4/3, or 5/3's the average rate of return in the banking industry, r^*).

In addition, we will supply you with a calculator which will allow you to find out your expected payoff by asking it questions about various scenarios of behavior by yourself and others without having to check the table yourself. Let's see how to use the tables.

Say that the average rate of return, r^* , in the banking industry is 7% and you were promised $r' = 12\%$. This would mean that if your money is in bank 4 or bank 5 then you

will be paid your promised amount no matter what the other subjects do. However, if your money is in a 1, 2, or 3, then you will not be able to be paid your promised amount if you wait until period 4 to take your money out. How much you then are paid will depend on when you take your money out, when the others do, and on the bank your funds are deposited in. Let us see how this will work.

Say you are contemplating taking your money out in Period 3 and you want to know what your expected payoff will be when 3 people removed their money in period 1, 2 in removed it period 2, and you alone remove it in period 3.

Assume $r^* = 7\%$ and $r' = 12\%$. To find out what your expected payoff will be in this scenario, the first thing you should do is turn to the table marked **Period 3** since that will be the relevant table for you. On the **Period-3** table you will see a set of columns marked, *number removing money in Period 1*, *number removing money in Period 2*, and *number of others removing money in period 3*. Look down the columns until you see the row indicating scenario just described. It is highlighted in Yellow. In other words, look for the Row that has a 3 in column 1, a 2 in column 2, and a 0 in column 3. If you look across that row you will see how much you will earn depending on where your money is deposited. For example, if your money is in bank 1 whose rate of return is 2.3% then under the above scenario you would earn 3.4 francs. Clearly, with such a poor bank if the others took their money out before you then there would be little left for you. However, if your money was in bank 5 (the best bank), whose rate of return is 11.6%, then you would earn 13.6 francs under the same scenario. (Note that this payoff is still below the promised return of 15.7 francs). You can look and see what your payoff would be in case your money was in any of the other banks. Since the bank your money is in is random, however, you could expect a return of 8.4 francs.

Let's take another scenario. Say that $r^* = 7\%$ and $r' = 12\%$ just as above. Say that you alone decide to take your money out in period 1, 2 people removed their money in period 2, 2 in period 3 and 1 in period 4. To find out what your payoff would be you must turn to the **Period 1** and look down the only column there to the row marked 0 indicating that you are the only one to remove at that time. As you can see your payoff would be 11.2 no matter what bank your funds are in since you will be paid your promised amount no matter what given all the funds in the bank and the fact that you alone are removing them. Under the same scenario say that instead of withdrawing your funds at period 1 you wait until period 3. In this case no people withdraw in period 1, 2 in period 2 and 3 in period three. To find your payoff here, look at the **Period 3** table and look at the row with a 0 in column 1, a 2 in column 2 and a 2 in column 3. Here we see that your payoff will be 12.9 francs if your money were invested in the worst bank but 14.0 if it were in the best bank. Your expected payoff from removing in period 3 is 13.8. So in this particular scenario, you would be better off removing your money in period 3 than in period 1. In other scenarios it could and would be different. To make sure you know how to use these payoff tables let us pause and have you answer the following questions.

Payoff Quiz

1) Find the payoff under the following situation:

The promised rate of return is $r' = 12\%$, the average rate of return is $r^* = 7\%$. You want to withdraw your money in period 3 and want to know your payoff if 3 people withdraw their money in period 1, 0 people in period 2, and you are the only person who withdraws in period 3. Look at your payoff table to find the answer under the assumption that your money is in the second best bank. Also find your expected payoff under this scenario.

The correct answer is 14.0 francs and 14.0 francs respectively for the second best bank and the expected payoff. If you did not get that answer try the next problem.

2) Find the payoff under the following situation: $r^* = 7\%$, $r' = 12\%$, everyone waits until the end of the experiment to withdraw his or her money and the money is deposited in the worst bank. Also find the expected payoff.

The answer is 11.2 for the worst bank and 13.2 for the expected payoff.

If you did not answer these questions correctly raise you hand and we will come by and assist you.

The Calculator

In order to make this process easier for you, we have provided you with a calculator that will enable you to find your hypothetical **expected** payoffs by simply feeding in scenarios into the calculator. (Note that this is your expected payoff and hence your actual payoff may differ since your funds will actually be in one and only one bank in any given round).

To enter the calculator simply click on the calculator button on your screen and you will be allowed to use it. When you click on the button you will see a screen that looks something like this.

Time Period Selection for Player 1:

☐ period 1 ☐ period 2 ☐ period 3 ☐ period 4

Time Period Selection for Player 2:

☐ period 1 ☐ period 2 ☐ period 3 ☐ period 4

Time Period Selection for Player 3:

☐ period 1 ☐ period 2 ☐ period 3 ☐ period 4

Time Period Selection for Player 4:

☐ period 1 ☐ period 2 ☐ period 3 ☐ period 4

Time Period Selection for Player 5:

☐ period 1 ☐ period 2 ☐ period 3 ☐ period 4

Time Period Selection for Player 6:

☐ period 1 ☐ period 2 ☐ period 3 ☐ period 4

Knowing which person or player you are enter any scenario by deciding how many other people you want to withdraw their money at various times. Note that it does not matter who withdraws at any time just the number of people doing it.

For example, lets look at our scenario above: You want to withdraw your money in period 3 and want to know your payoff if 3 people withdraw their money in period 1, 0 people in period 2, and you are the only person who withdraws in period 3. Say that you are player 6. One way to find your payoff is to assume that players 1,2, and 3 remove their money in period 1. Then click the period 1 button for each of them. Now click the period 3 button for yourself (player 6) and for players 4 and 5 click the period 4 button. By doing this you can find your expected payoff. (There are other ways to do it as well). This should give you an answer of 14.0 francs.

As a final example, find your expected payoff when you are Player 6, you and 2 others remove your money in period 2 and the remaining three other people remove their money in period 3. The answer should be 12.5 and if you did not get that answer please raise your hand.

At this point feel free to use the calculator and test yourself. It will remain available to you during the entire experiment.

Experimental Procedures

Now that you know the decision problem you will face, and how to calculate your payoff, let us explain how the exact experiment will proceed. After you have been assigned to a group of six subjects you will be awarded a fund of 10 francs which will be deposited into a bank account in one of five possible banks where the bank promises to pay you interest at the rate of $r' = 12\%$. **All people in your group will have their money deposited into the same bank.** The bank your money is deposited in will earn a rate of return of either $1/3r^*$, $2/3r^*$, $3/3r^*$, $4/3r^*$ or $5/3r^*$, where $r^* = 3/3r^*$ is the average rate of return amongst the five banks.

The first thing that happens in the experiment is that you are informed of the average rate of return among the five banks, i.e., you will be told r^* . This will occur by a message that will appear on your screen, which will say:

The Average Rate of Return is $r^* = 7\%$.

Next the computer will choose a bank into which to deposit your and all the other subjects' money, **but this will not be told to you.** All you will know is that there is an equal chance that your money will be in any one of the five banks.

Once this has occurred and you know your promised rate by the bank, $r' = 12\%$, and the average rate of return among the five banks $r^* = 7\%$, you will have to decide when you want to withdraw your money. Before you make your decision you will be able to consult both the payoff table available to you and use your calculator to ask and answer any questions you want. When you are finished consulting these aids and have decided on your decision, the computer will prompt you:

It is period 1 do you want to remove your money?

☐ Yes ☐ No 2

You will then click either **Yes** or **No** and click the submit button to confirm. If you click **Yes**, your participation in this round of the experiment will be over and you must wait for the others to finish. If you click **No**, after each subject has decided about Period 1 the computer will prompt you:

It is period 2 do you want to remove your money?

☐ Yes ☐ No 2.

This will continue for four periods. Once you and all the other subjects have entered and confirmed your decisions, you will be given some information about what happened in that round. More precisely, you will be told your payoff, the rate of return in the bank your money was deposited in (which will be $1/3r^*$ if it was deposited in the worst bank, $2/3r^*$ if it was deposited in the second worst bank, etc.), your promised payoff, the number of people who withdrew their money in each period, and their promised and actual payoffs. (Note that if any subject's payoff equals their promised payoff, it means that the bank had enough money to pay what they owed in that period). This will be the end of round 1.

Round 2 will then start in exactly the same way. In each round the promised rate of return (r') and average rate of return (r^*) will be identical. **(This means that for every round of the experiment $r^* = 7\%$ and $r' = 12\%$ and this will not change.)** However, in each round the computer will randomly determine the bank into which all subject funds are deposited by choosing among the banks with equal probability. Hence, there is an equal chance that the bank will be any one of the five possible banks. **It is important to note that the probability that any bank is chosen in round 2 (or any other round) is independent of what bank was chosen in the previous (or any preceding rounds. Each round is independent of the past.**

Again, you will be asked to choose a period when you want to remove your money and be prompted by the prompt:

Final Payoffs

Your final earnings in the experiment will be the sum of your franc payoffs earned during each of the 21 rounds. However, the first of the 21 rounds will be worth 20 times as much as each of the remaining rounds. This means that while in the first round each franc will equal \$1, each franc on the remaining rounds will be worth \$0.05 or five cents. The first round could be worth as much as \$15.75. Each of the remaining rounds are worth much less but their sum may still be substantial. You will be paid this amount when the experiment is over.

APPENDIX F

Payoff Table

Payoff Table for Sequential Low Information, $r^*=7\%$ and $r'=12\%$

Your Payoff if you withdraw at period 1

number of others removing money in period 1	Bank 1 rate=2.3%	Bank 2 rate=4.6%	Bank 3 rate=7%	Bank 4 rate=9.3%	Bank 5 rate=11.6%	Average Payoff
0	11.20	11.20	11.20	11.20	11.20	11.20
1	11.20	11.20	11.20	11.20	11.20	11.20
2	11.20	11.20	11.20	11.20	11.20	11.20
3	11.20	11.20	11.20	11.20	11.20	11.20
4	11.20	11.20	11.20	11.20	11.20	11.20
5	10.23	10.47	10.70	10.93	11.20	10.71

Your Payoff if you withdraw at period 2

number removing money in period 1	others removing money in period 2	Bank 1 rate=2.3%	Bank 2 rate=4.6%	Bank 3 rate=7%	Bank 4 rate=9.3%	Bank 5 rate=11.6%	Average Payoff
0	0	12.54	12.54	12.54	12.54	12.54	12.54
0	1	12.54	12.54	12.54	12.54	12.54	12.54
0	2	12.54	12.54	12.54	12.54	12.54	12.54
0	3	12.54	12.54	12.54	12.54	12.54	12.54
0	4	12.54	12.54	12.54	12.54	12.54	12.54
0	5	10.47	10.96	11.45	11.95	12.47	11.46
1	0	12.54	12.54	12.54	12.54	12.54	12.54
1	1	12.54	12.54	12.54	12.54	12.54	12.54
1	2	12.54	12.54	12.54	12.54	12.54	12.54
1	3	12.54	12.54	12.54	12.54	12.54	12.54
1	4	10.27	10.80	11.34	11.90	12.46	11.36
2	0	12.54	12.54	12.54	12.54	12.54	12.54
2	1	12.54	12.54	12.54	12.54	12.54	12.54
2	2	12.54	12.54	12.54	12.54	12.54	12.54
2	3	9.98	10.57	11.18	11.81	12.45	11.20
3	0	12.54	12.54	12.54	12.54	12.54	12.54
3	1	12.54	12.54	12.54	12.54	12.54	12.54
3	2	9.48	10.19	10.91	11.66	12.43	10.94
4	0	12.54	12.54	12.54	12.54	12.54	12.54
4	1	8.49	9.42	10.38	11.37	12.40	10.41
5	0	5.53	7.12	8.77	10.50	12.28	8.84

Your Payoff if you withdraw at period 3

number removing money in period 1	number removing money in period 2	number of others removing money in period 3	Bank 1 rate=2.3%	Bank 2 rate=4.6 %	Bank 3 rate=7%	Bank 4 rate=9.3 %	Bank 5 rate=11.6%	Average Payoff
0	0	0	14.05	14.05	14.05	14.05	14.05	14.05
0	0	1	14.05	14.05	14.05	14.05	14.05	14.05
0	0	2	14.05	14.05	14.05	14.05	14.05	14.05
0	0	3	14.05	14.05	14.05	14.05	14.05	14.05
0	0	4	12.86	13.76	14.05	14.05	14.05	13.75
0	0	5	10.72	11.47	12.25	13.07	13.92	12.29
0	1	0	14.05	14.05	14.05	14.05	14.05	14.05
0	1	1	14.05	14.05	14.05	14.05	14.05	14.05
0	1	2	14.05	14.05	14.05	14.05	14.05	14.05
0	1	3	12.87	13.92	14.05	14.05	14.05	13.79
0	1	4	10.29	11.13	12.02	12.94	13.91	12.06
0	2	0	14.05	14.05	14.05	14.05	14.05	14.05
0	2	1	14.05	14.05	14.05	14.05	14.05	14.05
0	2	2	12.88	14.05	14.05	14.05	14.05	13.81
0	2	3	9.66	10.63	11.66	12.75	13.88	11.72
0	3	0	14.05	14.05	14.05	14.05	14.05	14.05
0	3	1	12.89	14.05	14.05	14.05	14.05	13.82
0	3	2	8.60	9.80	11.08	12.42	13.84	11.15
0	4	0	12.95	14.05	14.05	14.05	14.05	13.83
0	4	1	6.48	8.14	9.91	11.78	13.76	10.01
0	5	0	0.12	3.15	6.39	9.84	13.51	6.60
1	0	0	14.05	14.05	14.05	14.05	14.05	14.05
1	0	1	14.05	14.05	14.05	14.05	14.05	14.05
1	0	2	14.05	14.05	14.05	14.05	14.05	14.05
1	0	3	13.14	14.05	14.05	14.05	14.05	13.87
1	0	4	10.51	11.31	12.14	13.01	13.92	12.18
1	1	0	14.05	14.05	14.05	14.05	14.05	14.05
1	1	1	14.05	14.05	14.05	14.05	14.05	14.05
1	1	2	13.24	14.05	14.05	14.05	14.05	13.89
1	1	3	9.93	10.85	11.81	12.83	13.89	11.86
1	2	0	14.05	14.05	14.05	14.05	14.05	14.05
1	2	1	13.45	14.05	14.05	14.05	14.05	13.93
1	2	2	8.97	10.09	11.28	12.53	13.85	11.34
1	3	0	14.05	14.05	14.05	14.05	14.05	14.05
1	3	1	7.03	8.57	10.21	11.94	13.78	10.31
1	4	0	1.22	4.01	6.99	10.17	13.55	7.19
2	0	0	14.05	14.05	14.05	14.05	14.05	14.05
2	0	1	14.05	14.05	14.05	14.05	14.05	14.05
2	0	2	13.61	14.05	14.05	14.05	14.05	13.96
2	0	3	10.21	11.06	11.96	12.91	13.90	12.01
2	1	0	14.05	14.05	14.05	14.05	14.05	14.05
2	1	1	14.00	14.05	14.05	14.05	14.05	14.04
2	1	2	9.33	10.38	11.48	12.64	13.87	11.54
2	2	0	14.05	14.05	14.05	14.05	14.05	14.05
2	2	1	7.58	9.00	10.51	12.11	13.80	10.60
2	3	0	2.33	4.87	7.59	10.50	13.59	7.78
3	0	0	14.05	14.05	14.05	14.05	14.05	14.05
3	0	1	14.05	14.05	14.05	14.05	14.05	14.05
3	0	2	9.70	10.66	11.68	12.75	13.88	11.74
3	1	0	14.05	14.05	14.05	14.05	14.05	14.05
3	1	1	8.14	9.43	10.81	12.27	13.82	10.89
3	2	0	3.44	5.73	8.19	10.82	13.63	8.36
4	0	0	14.05	14.05	14.05	14.05	14.05	14.05
4	0	1	8.69	9.86	11.11	12.43	13.84	11.19
4	1	0	4.55	6.59	8.79	11.15	13.67	8.95
5	0	0	5.65	7.45	9.39	11.48	13.72	9.54

Your Payoff if you withdraw at period 4

number removing money in period 1	number removing money in period 2	number removing money in period 3	number of others removing money in	Bank 1 rate=2.3%	Bank 2 rate=4.6%	Bank 3 rate=7%	Bank 4 rate=9.3%	Bank 5 rate=11.6%	Average Payoff
0	0	0	5	10.97	12.00	13.11	14.29	15.55	13.18
0	0	1	4	10.28	11.46	12.72	14.08	15.52	12.81
0	0	2	3	9.26	10.65	12.15	13.75	15.48	12.26
0	0	3	2	7.56	9.30	11.18	13.22	15.41	11.33
0	0	4	1	4.15	6.59	9.26	12.15	15.27	9.48
0	0	5	0	0.00	0.00	3.48	8.93	14.85	5.45
0	1	0	4	10.53	11.65	12.86	14.15	15.53	12.94
0	1	1	3	9.57	10.89	12.31	13.85	15.49	12.42
0	1	2	2	7.97	9.62	11.41	13.34	15.42	11.55
0	1	3	1	4.77	7.08	9.59	12.33	15.29	9.81
0	1	4	0	0.00	0.00	4.16	9.30	14.90	5.67
0	2	0	3	9.88	11.13	12.48	13.94	15.50	12.59
0	2	1	2	8.38	9.94	11.63	13.46	15.44	11.77
0	2	2	1	5.39	7.56	9.93	12.51	15.32	10.14
0	2	3	0	0.00	0.41	4.83	9.66	14.94	5.97
0	3	0	2	8.80	10.26	11.85	13.58	15.46	11.99
0	3	1	1	6.01	8.04	10.27	12.70	15.34	10.47
0	3	2	0	0.00	1.37	5.50	10.03	14.99	6.38
0	4	0	1	6.63	8.52	10.60	12.88	15.36	10.80
0	4	1	0	0.00	2.34	6.17	10.40	15.04	6.79
0	5	0	0	0.12	3.30	6.84	10.76	15.08	7.22
1	0	0	4	10.76	11.83	12.99	14.22	15.54	13.07
1	0	1	3	9.85	11.12	12.47	13.93	15.50	12.58
1	0	2	2	8.35	9.92	11.62	13.46	15.44	11.76
1	0	3	1	5.33	7.53	9.91	12.51	15.32	10.12
1	0	4	0	0.00	0.35	4.80	9.66	14.94	5.95
1	1	0	3	10.17	11.36	12.64	14.03	15.51	12.74
1	1	1	2	8.76	10.24	11.84	13.58	15.46	11.98
1	1	2	1	5.95	8.01	10.25	12.69	15.34	10.45
1	1	3	0	0.00	1.31	5.47	10.02	14.99	6.36
1	2	0	2	9.17	10.56	12.07	13.70	15.47	12.20
1	2	1	1	6.57	8.49	10.59	12.87	15.36	10.78
1	2	2	0	0.00	2.27	6.14	10.39	15.04	6.77
1	3	0	1	7.19	8.97	10.92	13.06	15.39	11.11
1	3	1	0	0.01	3.24	6.81	10.75	15.08	7.18
1	4	0	0	1.25	4.20	7.48	11.12	15.13	7.84
2	0	0	3	10.45	11.58	12.80	14.12	15.53	12.89
2	0	1	2	9.14	10.54	12.06	13.70	15.47	12.18
2	0	2	1	6.52	8.46	10.57	12.87	15.36	10.76
2	0	3	0	0.00	2.21	6.11	10.38	15.04	6.75
2	1	0	2	9.55	10.86	12.28	13.82	15.49	12.40
2	1	1	1	7.14	8.94	10.91	13.05	15.39	11.08
2	1	2	0	0.00	3.17	6.78	10.74	15.08	7.16
2	2	0	1	7.76	9.42	11.24	13.24	15.41	11.41
2	2	1	0	1.14	4.13	7.45	11.11	15.13	7.79
2	3	0	0	2.39	5.10	8.12	11.48	15.18	8.45
3	0	0	2	9.93	11.16	12.50	13.94	15.50	12.61
3	0	1	1	7.71	9.39	11.23	13.23	15.41	11.39
3	0	2	0	1.04	4.07	7.42	11.10	15.13	7.75
3	1	0	1	8.33	9.87	11.56	13.41	15.43	11.72
3	1	1	0	2.28	5.03	8.09	11.47	15.18	8.41
3	2	0	0	3.52	6.00	8.76	11.83	15.22	9.07
4	0	0	1	8.89	10.32	11.88	13.59	15.46	12.03
4	0	1	0	3.41	5.93	8.73	11.82	15.22	9.03
4	1	0	0	4.65	6.90	9.40	12.19	15.27	9.68
5	0	0	0	5.79	7.80	10.05	12.55	15.32	10.30

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